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Supporting Representation-Rich Problem-Solving in High School Physics

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SUPPORTING REPRESENTATION-RICH PROBLEM-SOLVING
IN HIGH SCHOOL PHYSICS

by

Lyrica L. Lucas

A THESIS

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SUPPORTING REPRESENTATION-RICH PROBLEM-SOLVING IN HIGH SCHOOL PHYSICS

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University of Nebraska, 2014

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The literature on physics education research (PER) promotes the use of multiple representations (such as pictures, diagrams, written explanations, and mathematical expressions) to enhance the problem-solving ability of students through instruction. The purpose of this study was to explore the use of a scaffolding strategy that involved the use of multiple representation tasks in problem-solving in a modeling physics class in high school. Another class with similar background was selected as a comparison group. In 12 in-depth problem-solving interviews of students drawn from the two classes, I investigated in detail how the students responded to the multiple representations tasks and how it affected their problem-solving performance, use of representations, and the quality of their representations compared to students who were not guided to generate representations in solving similar problems. Aggregate data on student problem-solving performance and use of representations was collected from 14 study problems and cross-checked with findings from cognitive interviews. I found that more students from the scaffolding group constructed visual representations in their problem-solving solutions, while their use of other representations did not differ with that of the comparison group.

Despite the increase in the use of visual representations, there was no observed improvement in problem-solving performance relative to the comparison group. Also, analysis of the problem-solving work of the relatively successful problem solvers in both

groups showed that their visual representations are accurate translations of physics concepts. The data from the interviews revealed that students do not believe that it is necessary to write down physics concepts because visual representations help them more in problem-solving. I found that the relatively similar performance in problem-solving of both groups can be attributed to shared misconceptions and common novice-like problem-solving behaviors that were not addressed by the utilized scaffolding strategy.

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CHAPTER 1

INTRODUCTION

A major goal of most high school physics courses is to provide the students with a clear and logical presentation of the basic concepts and principles of physics and to strengthen an understanding of the concepts and principles through a broad range of applications that involve problem-solving. Several fields of study aside from physics such as engineering, architecture, biology, medicine, mathematics, and teaching require problem-solving as a requisite skill. Thus, developing problem-solving skills early on in a student's education is vital regardless of the career path in which the student eventually applies his or her knowledge and skills.

Physics textbooks and curriculum materials used in schools show that problem-solving is known to be an intrinsic part of any physics course. Problem-solving guides and examples of solved problems are commonly included in physics textbooks and physics teachers usually expect that students learn from these examples. It should be noted, however, that recent studies reveal that students increasingly find textbooks as the least helpful component of a physics course compared to other components such as homework and lecture discussions (Sadaghiani, 2011; Brooks et al., 2009; Cooney et al., 2002). Also, instructional environments vary depending on the pedagogical approach adopted by a physics teacher. There are documented cases of problem solving instruction that fail because little attention is given to requisite modes of reasoning and instead focus

primarily on the use of mathematics, leading students to prefer formula-centered problem-solving methods (Hestenes, et al., 1992).

To help students understand physics concepts and solve problems, the literature on physics education research (PER) endorses the use of multiple representations (Etkina, et al., 2009). Kohl and Finkelstein (2008) noted that “representations” can both refer to external and mental representations. Both types of representations have been the subject of various studies in physics education. The use of representations to make a problem solving task easier is found to be an expert-like approach. Experts are observed to typically start with visualizing the problem and performing the conceptual analysis and planning steps before resorting to the implementation of the plan, while novices may simply look for plausible formulas without regard to applicability of concepts (Mason & Singh, 2011).

Physical quantities and concepts can often be visualized and understood better by using concrete or external representations referring to the various ways of depicting objects and processes such as written language, diagrams, equations, graphs, and sketches. These concrete representations assist qualitative and quantitative reasoning. Studies on the interplay between the use of representations and problem-solving serve as a window to students’ mental representations and in so doing, give educators the opportunity to develop tools necessary to produce a more coherent understanding of how students solve physics problems.

The findings of PER on the multiple differences in the approaches of experts and novices to problem solving have led to an interest in studying how expert-like

characteristics in problem solving develop and whether the development is a gradual process or if it is a result of certain types of exposure or instructional scaffolding. Several studies suggest that effective problem solving skills may be cultivated by implementing scaffolding supports (Bao et al., 2011; Lin & Singh, 2011). Similarly, exposure to a learning environment also has a significant role in the development of problem solving skills. Kohl and Finkelstein (2006) found that a pervasive use of different representations and multiple representations by teachers in a learning environment appear to broaden the representational skills of students. These results serve as a valuable source of information for research-based instruction models such as the *Modeling Instruction Program*. Recently, in the U.S. there have been many professional development programs available to teachers to learn how to use a modeling instruction approach.

1.1 Background Literature

This study seeks to understand how a guided approach for the use of multiple representations affects the problem solving performance and use of multiple representations of physics students at a public U.S. Midwestern high school. The design of this study is based on the results of other recent PER findings. Physics education researchers have been interested in understanding the effects of using a problem-solving heuristic and the differences between expert and novice learners. Studies in this area have led to the development of pedagogical strategies in problem-solving; the physics education community began to consider ways of helping students to solve problems. The

literature on problem-solving is robust, but I only looked into the work of researchers that involved the use of multiple representations.

Since this study is within the field of problem-solving research, it is necessary to adopt a definition for problem-solving. The National Council of Teachers of Mathematics (NCTM) identified problem solving as one of the five fundamental mathematical process standards (NCTM, 2000). The NCTM defines problem-solving as engaging in a task for which the solution is not known in advance. In physics education, the emphasis on problem solving as opposed to rote acquisition of knowledge is easily verified by examining physics textbooks and common course syllabi. Problem-solving is emphasized in textbooks through recurrent displays of examples interwoven throughout the text. Mathematical and scientific activities involve problem-solving, which is why it is necessary to study and understand its intricacies.

1.1.1 Emphasis on Multiple Representations in Research-based Curricula

Curricular developments in the field of promoting the use of multiple representations resulted from the recommendation of physics education literature. For instance, Heuvelen (1991) developed a curriculum called *Overview, Case Study Physics* (OCS) that was based on the use of representations. Heuvelen's work was grounded on research in problem-solving and multiple representations (Larkin, et al., 1987; Heller & Reif, 1984). Students who received instruction in OCS were found to be more likely to correctly solve a problem and they exhibited greater qualitative reasoning as evidence by the correct use of physics principles, free-body diagrams, and vector components. In the

OCS curriculum, the instructor uses representations such as pictures, words, diagrams, and graphs to help students understand a concept and then students use these representations to solve quantitative problems based on this concept. Students' learning gains on a diagnostic test from the OCS course were 15% higher than those in a traditional class, and the OCS students were also able to retain information longer (Etkina et al., 2009).

Like OCS, Modeling Instruction also puts emphasis on the use of multiple representations. Modeling Instruction is an evolving, research-based program for high school science education reform that was supported by the National Science Foundation (NSF) from 1989 to 2005. Teachers participate in a series of workshops and acquire robust teaching methodology for developing student abilities to make sense of physical experience, understand scientific claims, articulate coherent opinions of their own and defend them with cogent arguments, evaluate evidence in support of justified belief. In a comparative analysis of Force Concept Inventory (FCI) test scores, it was found that teachers who utilize the modeling method most fully have the highest student posttest FCI mean scores and gains (Dukerich et al., 2008). The FCI instrument was designed to evaluate student understanding of the fundamental concepts in Newtonian physics (Hestenes et al., 1992).

These examples of research-based curricula aim to correct the weaknesses of traditional lecture-demonstration classroom environment. According to Hestenes et al., (1995), the bane of traditional instruction is that most students cling to a "plug-and-chug" problem-solving strategy that severely limits their skill development. The initial

qualitative analysis of the problem, including the construction and use of suitable diagrams is the key to effective problem-solving.

1.1.2 The Role of Using Multiple Representations in Problem Solving: Cognitive Theory Perspectives

It is relevant to review the findings of studies on the similarities and differences between experts and novices in problem solving and their use of multiple representations. It has been shown that experts are able to smoothly use multiple representations and move between representations when they are thinking and sharing ideas (Kohl & Finkelstein, 2008; Kozma, 2003). Also, the expert-like use of multiple representations has been argued to be an important goal of physics education for successful problem solving and a strong conceptual understanding (Heuvelen & Zou, 2001). Having a clearer picture of how experts and novices differ in their approaches to multiple representation problem solving will allow us to better bridge the expert-novice gap with education.

1.1.2.a. Expert-Novice Research on Problem Solving

Two forms of problem solving knowledge are often described in expert-novice research (Gagne et al., 1993). The first one is declarative knowledge, which refers to knowledge of facts, theories, events, and objects. The other is procedural knowledge that includes motor skills, cognitive skills, and cognitive strategies. When problem solving occurs, both declarative and procedural knowledge are activated in working memory and interact in a variety of ways. Nonetheless, studies show that general problem solving knowledge is an incomplete explanation of how problem solving occurs.

Expert–novice research reveals that experts use domain knowledge, basic automated skills, and domain-specific expertise in problem solving (Abel, 2003; Gerace, 2001; Chi et al, 1981; Larkin et al, 1980). Experts were found to exhibit better conceptual understanding of their domain, use more automated skills and domain-specific strategies and have a declarative conceptual understanding and procedural basic skills and strategies.

The actual information in memory and the organization of that information in memory defines an individual's conceptual understanding in a domain. This can be related to the schema theory: information is stored in memory as knowledge structures and frameworks and activated to provide a lens through which to view new information (Norman, 1992; Gagne, 1985). A problem solver may also perform necessary and routine operations without much thought using basic, automated skills. These skills have been mastered by the problem solver that they have become habitual and may even be unconsciously applied in the problem solving process allowing an individual to operate quickly and accurately. The expert's speed and skill of execution compared to a novice is explained by the use of automaticity (Chi et al, 1988). Unlike basic, automated skills, the problem solver may also use domain-specific strategies that remain under conscious control. These strategies refer to the processes in a domain that the problem solver must consciously think about in order to solve a problem.

Expertise relies on both domain-specific knowledge and problem-solving skill. From this standpoint, experts and novices can be observed to manifest problem solving behaviors that can be associated to conceptual and procedural knowledge. A summary of

main differences between experts and novices in problem solving by Gerace (2001) is listed in the following table.

TABLE 1

Summary of Major Differences between Experts' and Novices' Problem-solving Behavior and Characteristics of Declarative Knowledge from Problem-solving Studies

Expert	Novice
Problem Solving Behavior	
Conceptual knowledge impacts problem solving	Problem solving largely independent of concepts
Often performs qualitative analysis, especially when stuck	Usually manipulates equations
Uses forward-looking concept-based strategies	Uses backward-looking means-ends techniques
Has a variety of methods for getting unstuck	Cannot usually get unstuck without outside help
Is able to think about problem solving while problem solving	Problem solving uses all available mental resources
Is able to check answer using an alternative method	Often has only one way of solving problem
Declarative Knowledge Characteristics	
Store of domain specific knowledge	Sparse knowledge set
Knowledge richly interconnected	Knowledge mostly disconnected, Amorphous
Knowledge structured hierarchically	Knowledge stored Chronologically
Integrated multiple representations	Poorly formed and unrelated representations
Good recall	Poor recall

It is important to note that experts and novices differ on their perception of a problem's difficulty because experts use external representations to support mental representations. Experts successfully use representations as cognitive tools to help construct understanding; instead of processing everything internally, students can create an external representation to reduce the cognitive load (Nieminen et al., 2012). From this

perspective, the use of representations is very important to make a problem solving task easier by reducing cognitive load. Unfortunately, this idea is not shared by many students. An outlook on problem-solving that is prevalent among students who can be characterized as novice problem-solvers is described by Hestenes et al., (1995): “The student sees that the answer to a problem invariably comes from plugging numbers into equations and chugging a little arithmetic, all that fluff about diagrams and physical intuition can be ignored, and the key to problem solving is finding the right equation in which to plug the given numbers.”

1.1.2.b. Cognitive Theory Perspectives

The difference between experts and novices can be viewed from the perspective of Cognitive Learning Theory (CLT). Most theories of human problem solving consist of some formulation of the following seven stages: (1) problem categorization, (2) construction of a mental representation of the problem, (3) search for the appropriate problem-solving operators (e.g., strategies or procedures), (4) retrieval and application of those operators to the problem, (5) evaluation of problem-solving progress and solution, (6) iterating stages 1–4 if not satisfied with progress/solution, and finally (7) storage of the solution. These stages may not be strictly sequential, but may be iterative (Chi et al., 2010). They show that cognitive psychologists view problem solving as a process that includes introspection, observation, and the development of heuristics.

Characteristics of experts and novices can be understood by looking into these stages. For instance, in problem categorization tasks, representations play a significant role in the way experts and novices differently categorize physics problems. Experts

based their categories in terms of physics principles used in solving them while novices are distracted by the context or surface features of problems and therefore put inclined planes and pulleys in separate categories (Chi et al., cited by Mason & Singh, 2011).

CLT focuses on information processes which are governed, or constrained, by the Information Processing System (Newell, 1972). This theory stands in contrast to Behavioral Learning Theory (BLT), which focuses on stimulus-response associations. CLT gives emphasis to the role of working memory capacity, organization of long-term memory, and cognitive retrieval of relevant information when an individual is engaged in the several separate activities in the process of problem solving such as creating patterns, interpreting figures, developing geometric constructions and proving theorems.

Differences between experts and novices can also be better understood by reviewing Gagne's taxonomy of learning outcomes. Within the cognitive domain of Gagne's (1985) taxonomy, intellectual skills, verbal information and cognitive strategies are identified as categories of capabilities. Knowing how to do something involves the use of intellectual skills, which can be essentially referred to as procedural knowledge. The ability to communicate facts by writing, speaking, or drawing involves the processing of verbal information is the use of declarative knowledge. Cognitive strategies refer to the capabilities to control processes such as remembering information or concepts and solving problems. In PER, differences in these categories of capabilities within the cognitive domain are described in studies concerning the problem solving approaches of experts and novices (Chi et al, 1981; Abel, 2003; Larkin et al, 1980; Gerace, 2001).

1.1.2.c. Heuristics

As a complex cognitive activity, cognitive psychologists provide different descriptions of problem solving. Historically, Polya (1973) defined mathematical problem solving as a process that involved several dynamic activities: understanding the problem, making a plan, carrying out the plan, and looking back. These activities or general problem solving strategies have also been referred to as heuristics (i.e. the general methods used in problem solving). Polya (1973) was known for promoting the idea that the application of general problem solving strategies was crucial to problem solving expertise. Although his work was monumental and has been the foundation on which much of the work in problem solving heuristics has been based, Schoenfeld (1985) extended the interpretation of problem solving to not only consider heuristics, but to take into account a larger framework that includes resources (base knowledge), heuristics (problem-solving techniques), control (selecting and deploying of resources), and belief systems (misconceptions, attitudes).

As elaboration on problem solving continued various cognitive heuristics approaches were developed (Reif, Larkin, & Bracket, 1976; Larkin, 1981; Heller & Reif, 1984; Heuvelen, 1991; Leonard, Dufresne, & Mestre, 1996; and Beichner, 1997). In recent years, the use of representations has been integrated in cognitive approaches to accommodate research findings on the differences between experts and novices. For instance, Heller, Keith & Anderson (1992) suggested that students should make a systematic series of translations of a problem into different representations, each in more abstract and mathematical detail. They promoted the use of five steps: (1) visualize the

problem, (2) describe the problem in physics terms, (3) plan a solution, (4) execute the plan, and (5) check and evaluate. Reference textbooks in introductory physics typically include a problem solving guide based on research-based cognitive heuristics approaches.

Experts and novices differ in their use of representations when they apply heuristics to problem solving. Larkin (1981) found that experts almost always draw a picture to visualize the problem and then creates a conceptual representation (e.g., free-body diagram) to describe the problem in physics terms while novices typically jump to executing a plan (Heuvelen, 1991). Research-based curricula in the recent years have had a great impact in addressing this difference. In a study by Etkina, et al., (2009) using two multiple choice physics problems, 17% of students from a traditional introductory course constructed a diagram compared to 68% of students from a course that promoted the use of representations.

1.1.3 Scaffolding Supports in Physics Education

Anderson (cited by Frederiksen, 1984) describes in detail a theory about the acquisition of problem-solving expertise that involves three stages: (1) *declarative stage*, during which the learner receives instruction that is encoded as a set of facts; the information may be used to generate behavior, but the retrieval of the relevant facts must be rehearsed to keep them available; (2) a *knowledge compilation stage*, during which the knowledge is converted into a set of procedures that can be carried out without any interpretive operations; and (3) a *procedural stage*, during which the activity can be carried out autonomously. Instructional scaffolding adheres to this theory and the theories

in cognitive learning and problem solving that I have described in the previous sections. When concepts and skills are first introduced to students, opportunities to practice should be established in the learning environment.

The development of scaffolding supports in challenging learning environments has become a flourishing theme in PER as researchers continue to seek effective ways in developing expert-like problem solving behaviors among students. Podolefsky & Finkelstein (2007) reported the effectiveness of a curriculum that builds on analogical scaffolding. Bao et al., (2011) found that conceptual scaffolding in solving synthesis problems (i.e., problems combining two major topics that are broadly separated in a teaching timeline) encouraged students to search for and apply appropriate fundamental principles, and that repeated training using synthesis problems helped students to make cross-topic transfers. Lin & Singh (2011) showed how isomorphic problems could be used to design different types of scaffolding for problem solving. All of these studies highlight the relevance of constructing effective scaffolding supports. Since the development of expert-like traits occurs in stages, the goal of instruction should be to help the students make successful transitions from one stage to the next.

1.2 Rationale

There are a variety of challenges that physics students confront in the process of problem solving. Physics teachers encounter numerous cases of students attempting to solve physics problems, but are unsure how to start, how to proceed, or how to interpret the problem correctly. Similarly, there are also students who can immediately explore a

problem and develop a better understanding of underlying physics concepts by choosing a variety of strategies. The difference in problem solving abilities among students is an important issue to be addressed. Teachers must constantly develop and select instructional methods and design scaffolding supports that aim to better bridge the performance gap among students.

The starting point for this vein of work was identifying problem solving aspects of the high school physics course in which the students may be supported to practice the use of multiple representations. In order to develop students' representational skills as they apply to problem-solving, we should attempt to create an instructional environment that encourages the use of multiple representations across all aspects of the course (Kohl and Finkelstein, 2006).

The Modeling Instruction Program has embedded scaffolding supports for the use of multiple representations in laboratory activities (See Appendix A). I wanted to look into other aspects of the high school physics course that involved problem-solving and study how problem solving performance and use of multiple representations might be affected if the use of multiple representations in problem solving is constantly encouraged. Aside from problem-solving activities integrated in laboratory investigations, students are expected to solve physics problems, usually called “warm-up exercises” during large-group meetings and to work on sets of homework problems. The fading of scaffolding supports in these activities may be justified if the students have mastered the skill of using multiple representations. However, this may be too much to ask of physics students considering the short amount of time given to them to learn

fundamental physics knowledge and skills. Lin and Singh (2011) found that a common difficulty among introductory physics students working on a quiz problem was that they did not draw a free-body diagram, resulting in many mistakes in their analyses. They also observed that the students did not develop a habit of drawing an acceleration vector.

Developing expert-like traits in problem solving and in any domain takes time. Much research shows that a minimum of 10 years of daily deliberate practice is necessary to develop expertise in most domains (Ericsson et al., 1993). Ericsson and colleagues referred to deliberate practice as repeated experience in which the individual can attend to the critical aspects of the situation and incrementally improve his or her performance in response to knowledge of results, feedback, or both from a teacher. This perspective suggests that in order to develop problem solving skills such as the use of multiple representations, we can explore the use of instructional scaffolding that focuses on deliberate practice.

In high school physics, students begin to encounter mathematical problems that are multistep and require some systematic approach. Most standardized tests in science and math include multistep problems to evaluate conceptual knowledge. Unfortunately, recent trends in evaluation that focus on test scores may not reveal how the use of representations affects the problem solving performance of students. In this study, I collected data from homework and interviews to understand how students use multiple representations in solving multistep problems. Since the literature in PER and the framework supporting the modeling instruction program suggest that expert-like problem solving skills such as the use of multiple representations may be supported by target

training, I selected specific problem-solving tasks that point to the use of multiple representations and formed a checklist of these tasks for the students to use. Performing these tasks during problems solving could serve as a scaffolding support for the sustained use of multiple representations in problem solving.

1.3 Research Questions

The purpose of this study is to explore the role of using a guided scaffolding approach for generating representation-rich solutions to problems in a high school physics course. Guided scaffolding involved the use of specific problem-solving tasks, which are assumed to lead the students in using various representations (e.g., verbal, mathematical, pictorial, graphical) that may assist students' sense-making. This study investigates three questions:

1. How does the scaffolding strategy of using problem solving tasks affect the: (a) students' use of representations, (b) students' performance in problem solving, and (c) quality of the representations they used?
2. How do students address the problem solving tasks in the process of solving problems? Which representations do they use and how do they use them?
3. What differences in misconceptions and problem solving behaviors related to the use of representations, if any, can be observed?

The answers to these questions provide insight about the use of multiple representations in teaching and learning physics in high school. Quantitative and qualitative data were used to analyze how students can be further supported to use

multiple representations in problem solving. A better understanding of how problem solving takes place can allow us to develop research-based pedagogical approaches that are responsive to the needs of our students.

CHAPTER 2

METHODOLOGY

2.1 Context

This study was conducted in selected algebra-based physics classes during an 18-week-long semester at a public, U.S. Midwestern, high school. The school operates on a 4x4 block schedule, a type of academic scheduling in which a student has fewer classes per day, but each class is scheduled for a longer period of time than normal (i.e., 90 minutes). A block section physics class meets every day and students finish the course within one semester. Two classes taught by a high school teacher who uses the Modeling Instruction curriculum were selected for this study. The physics course offered by the teacher uses a broader selection of representations than a comparable traditional course. The course aims to provide students with a clear and logical presentation of the basic concepts and principles of physics and to strengthen an understanding of the concepts and principles through a broad range of applications.

Modeling instruction is a reform effort that has had great success at the high school level, which emphasizes active student construction of conceptual and mathematical models in an interactive learning community through the use of activities that are focused on the process of building, validating, and deploying models (Brewer et al., 2009). Modeling instruction is organized into modeling cycles with two main stages: (1) model development and (2) model deployment (Dukerich, et al., 2008). Model development typically begins with a demonstration and class discussion with the goal of

establishing a common understanding of a question to be asked of nature. Then, in small groups, students collaborate in planning and conducting experiments to answer or clarify the question. At this stage, it should be noted, that the model puts emphasis on the use of multiple representations. Students present and justify their conclusions in oral and written form, including the formulation of a model for the phenomena in question and an evaluation of the model by comparison with data. Technical terms and representational tools are introduced by the teacher as they are needed to improve models, facilitate modeling activities, and improve the quality of discourse. In the model deployment stage, students apply their newly-discovered model to new understanding by working on challenging worksheet problems in small groups, and then they present and defend their results to the class with the use of portable whiteboards. Students also complete quizzes, tests, and lab practicums to demonstrate their understanding of the model. The use of multiple representations is further promoted by asking students to offer brief explanations of their strategies when solving problems.

2.1.1 Participants

This study had two data gathering phases: (1) collecting problem solving work of students ($n=43$) for a period of 10 weeks and (2) interviewing selected students ($n=12$). The students were enrolled in an honors physics course that uses the Modeling Instruction curriculum. The students in this study were in two sections with the same teacher to eliminate instructor effects when comparisons between the sections are made. I arbitrarily assigned one section as the scaffolding group (SG) and the other section as the comparison group (CG). I gathered demographic data at the beginning of the semester to

present the characteristics of both groups. It is important to compare the two groups on various measures since it was not possible to randomly assign students to which group they would belong. The sample of this study was a convenience sample. They were selected by virtue of being the students of the high school teacher who have agreed to collaborate with the researcher.

TABLE 2

Distribution of Students by Age, Year Level, and Sex

Characteristics	Scaffolding Group, % n = 23	Comparison Group, % n = 20
Age		
15-16	17	8
17-18	83	60
Year Level		
Sophomore/Junior	30	50
Senior	70	50
Sex		
Male	39	40
Female	61	60

Table 2 shows the distributions of students in both groups by age, year level, and sex. The average age of the SG students was 17.04 (SD=0.13) while that of the CG students was 16.65 (SD=0.17). In both groups, 17 is the most common age. Majority of the students (60%) were in their senior year. More of them were female (60%).

At the beginning of the semester, students from both groups were asked to complete a Student Information Sheet (SIS) (Appendix B). The Force Concept Inventory (FCI) (Appendix C) and Maryland Physics Expectations Survey (MPEX) (Appendix D)

were also administered to both classes to respectively gauge their physics background knowledge and attitudes toward the subject.

2.1.1.a Ethical Considerations

The participants in this study are still considered minors. Parent permission was obtained before the students were allowed to participate in the study. Since there were two phases of data collection, parental consent forms approved by the Lincoln Public Schools Institutional Review Board (IRB) were sent to the parents of prospective participants for each phase and only the students who have obtained permission from their parents were invited to participate in the study. To make sure that the students were voluntarily participating in the study and not coerced to do so, they were fully informed about the procedures involved in the study. The contents of the youth assent form were discussed before data was collected (i.e., at the beginning of the semester in the first phase and before the conduct of an interview in the second phase) to inform the students that there is no obligation at all for them to participate in the study and that they can withdraw at any time.

To safeguard the identity of the research participants, pseudonyms were used to keep each person anonymous. I also kept all materials confidential, securing digital copies of documents and audio-video files in a password-protected computer and hard copies of written transcripts and student problem solving work in a locked filing cabinet.

2.2 Methods of Investigation

In this section, I described the design of the study, the instruments I used, and how I analyzed the data. I also addressed the issues of validity and reliability through a discussion of methodological issues and limitations of the study.

2.2.1 Research Approach

This study employed a multi-method research design to explore the effects of a scaffolding strategy for the use of multiple representations in physics problem-solving.

2.2.1.a Structure of the Study

There were two phases in this study as shown in Figure 1. In Phase 1, two high school physics classes with a common teacher were identified as the research population. Random assignment of students to groups was not possible so pre-existing classes were used. One class was arbitrarily identified as the Scaffolding Group (SG) and the other class as the Comparison Group (CG). Student background data was collected from both groups using survey instruments administered during the first week of class to ensure that the two groups shared similar characteristics. A total of fourteen (14) homework problems were given to both groups within a period of 10 weeks. At least one problem was given each week, two problems at most. The checklist of problem solving tasks was introduced by the teacher to the SG students as a scaffolding strategy for the use of multiple representations.

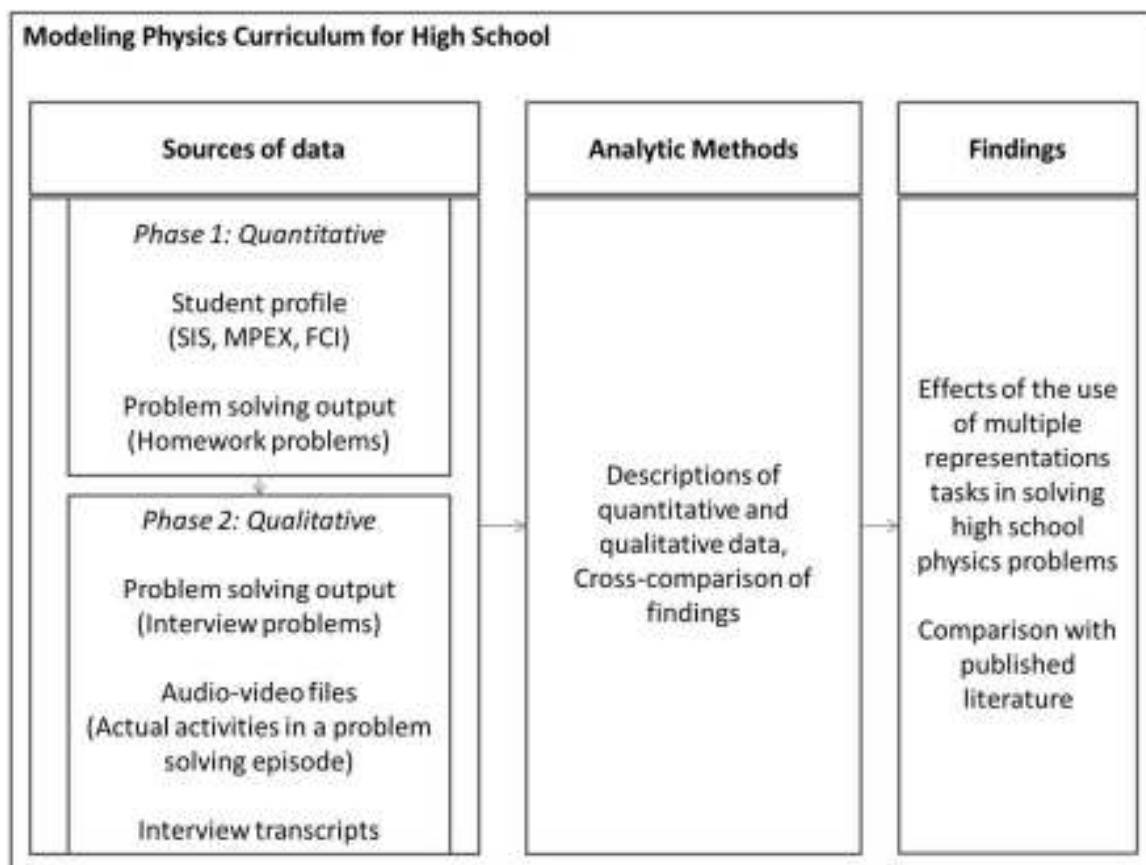


FIGURE 1. Structure of the Study. The figure shows the two phases of the study.

In Phase 2, a purposeful sample of 12 students was selected for cognitive interviews. For this study, I used the data from six SG students and six CG students. My aim was to sample heterogeneity in the use of multiple representations in problem solving. I used maximum variation sampling to capitalize on diversity relevant to my research questions. The six students from each group were comprised of more successful problem solvers and less successful problem solvers in their respective groups.

The research was exploratory; therefore, the findings that I have described in this study are not definitive. This study will tell us where to look in attempting to understand the use of representations in problem solving. That is, the patterns found in the multiple

sources of data can be used to guide future research agenda, both qualitative and quantitative, in addressing the problems that have been identified in this study.

2.2.1.b Researcher Statement

Merriam defines the researcher's position as the process by which the researcher puts forth his or her biases, assumptions, and experiences (Merriam, 2009). I am a graduate student pursuing a Master's degree in teaching and learning, and teacher education. I have previously worked on a Master's degree in physics to enhance my background in physics education. As a researcher, I assume a learning role rather than a testing one and view my work within the post-positivist paradigm. I conduct my research among other people, learn with them, rather than conduct research on them. When managing interviews, I strive to engage in social construction of a narrative with respondents to activate their stock of knowledge. The open-ended and exploratory character of post-positivist research leads me to understand the nature of problems that I set out to investigate. In this study, I aim to understand how the students' use of multiple representations in problem solving might be supported rather than try to control or resolve issues in problem solving.

My prior experience as a physics instructor in a different cultural setting can potentially intrude with my data collection and analysis; thus, it is necessary to broaden my perspective. Since 2012, I have been observing physics classes at the high school where I planned to conduct research to familiarize myself with the curriculum and classroom culture. This experience has allowed me to build a working relationship with

the high school physics teacher and eventually facilitated my transition from learning about the educational setting to conducting classroom-based research.

In this study, I must acknowledge that I interacted with the participants as an observer despite my efforts to distance myself from any causal effect on the outcomes. Because of this, the research may be value-laden. That bias, however, does not attempt to force specific results, but should be interpreted based on the research paradigm that I subscribe to as a researcher. Also, my judgment of the students as individuals is limited since I was mainly focused on their cognition.

2.2.2 Instruments

The research questions in this study were examined in several parts: problem solving performance, use of multiple representations, and the quality of representations used in problem solving. In order to understand how the scaffolding affects each of these components, it is necessary to examine each of these separately. Thus several different instruments were used.

2.2.2.a Student Information Sheet (SIS), Maryland Physics Expectations Survey (MPEX), and the Force Concept Inventory (FCI)

This set of instruments was used to determine how similar the two groups were based on a number of background variables. All of these instruments were administered to all students during the first week of class. The SIS was designed to gather demographic data. From the SIS, I was able to gather data on age, year level, sex, feeling of

preparation for the course, high school math background, expected grade in the course, and expected amount of study time.

The MPEX was used to gauge the attitudes, beliefs, and expectations of students that have an effect on what they learn in an introductory physics course. The MPEX was developed at the University of Maryland by Redish et al. (1998). In the survey, students are asked to agree or disagree on a five point scale with 34 statements about how they see physics and how they think they work in their physics course. The authors have given the survey to a group of experienced university faculty committed to reforming their teaching to increase its effectiveness and have used this group's response as their definition of "expert" responses (Appendix E). In interpreting MPEX results, the authors of the survey referred to a response that agrees with that of the "expert" as "favorable" and the response that disagrees with that of the "expert" as "unfavorable".

The FCI is a widely used physics test of students' conceptual understanding of forces. The 30-question multiple-choice test has been demonstrated to be valid and reliable. The FCI is regularly administered by the high school physics teacher in this study as an overall measure of effectiveness of instruction. The FCI data for the two groups were taken from the teacher's class record.

2.2.2.b Homework Problems

The homework problems used in these activities are selected from the pool of the end-of-chapter (EOC) problems in the adapted textbook for the high school physics course. A total of 14 homework problems were collected for 10 weeks. In some weeks, students were asked to solve one problem and in other weeks they were given two

problems depending on the lessons that were already discussed in class. Both groups solved the same sets of problem. I coordinated with the teacher to select problems that are well-defined (i.e., problems with discrete representations and finite goals). Also, the problems were multistep and situational; solving them would require both qualitative and quantitative analyses. Figure 2 shows one of the problems used in this study.

Two soccer players start from rest, 48 m apart. They run directly toward each other, both players accelerating. The first player has an acceleration whose magnitude is 0.50 m/s^2 . The second player's acceleration has a magnitude of 0.30 m/s^2 . (a) How much time passes before they collide? (b) At the instant they collide, how far has the first player run?

FIGURE 2. Example homework problem used in the study.

At the beginning of the semester, I created a pool of problems with solutions and gave them to the physics teacher for review. This step was necessary since the teacher knew which topics were already discussed in class, thus he was in a better position to evaluate which problems should be assigned to the students on a certain week. Some problems (i.e., “Box” and “Bricks”, See Appendix F) were added by the physics teacher from his teaching unit.

2.2.2.c Checklist of Problem Solving Tasks

The checklist of problem solving tasks was introduced by the high school physics teacher to all the SG students (Appendix G). A copy of the checklist was attached to the weekly homework problems described in the previous section. The checklist was also used by the SG students who were interviewed in the second phase of data collection.

The checklist includes eight tasks that were designed to influence students' problem solving by creating awareness about multiple representations that can be used in problem solving. Visual representations, reasoning in written language and mathematical

representations are the expected outputs from the SG students along with a numerical solution to well-defined physics problems. The components of the checklist are as follows:

A. Visual representations

The students were expected to produce a visual representation with the following prompts:

1. Draw a diagram(s) that represents your understanding of the problem (chart, graph, sketch, free-body diagram, picture, arrows).
2. Label the diagram(s) with symbols of physical quantities given in the problem.

These tasks were included in the checklist because using visual representations is typical among expert problem solvers. Thus, students should be given opportunities to practice generating visual representations in problem solving. Silver and Stylianou (cited by Etkina et al., 2009) investigated the role of visual representations in advanced mathematical problem solving and they found that experts not only constructed visual representations more frequently but used them to explore the problem space, develop a better understanding of the situation, and to help solve the problem.

B. Reasoning expressed in written language

The students were expected to express their reasoning in written language with the following prompts:

1. Identify the key physics concepts that you think are relevant to solving the problem.

2. Briefly explain how you will use the key concepts in your procedure for solving the problem and evaluating if your answer is correct.

These tasks were included in the checklist because it is important to teach to identify underlying key concepts in physics problems and create opportunities for them to explain how these key concepts could be used to solve a given problem. This is the reason why students are asked to justify their conclusions from laboratory investigations in oral and written form. Studies show that beginners in physics have difficulties in describing a general approach for solving a given problem and typically attempt to solve them by finding and manipulating equations (Dufresne et al., 1996).

The ability to describe the approach that one would take in order to solve a problem is an archetypal expert trait. Experts typically describe a problem solving approach by including the identification of physics concepts or principles together with the rationale for why they apply, and a general procedure for applying them.

C. Mathematical representations

The students were expected to use mathematical representations with the following prompts:

1. Identify the equations that you would need.
2. Derive the mathematical model that you would need to use in order to find a numerical solution.

In the process of constructing mental representations of a problem, experts use different concrete representations to aid reasoning (Chi et al., 2010). Mathematical representations assist both qualitative and quantitative reasoning and problem solvers

typically move in and out of representations to make connections with multiple ideas.

Hestenes *et al.* (1995) suggested that problem-solving performance can be improved by making the model in every problem explicit.

D. Numerical Output

The students are expected to arrive at a numerical solution:

1. Identify the numerical values of the physical quantities given in the problem.
2. Perform the appropriate operations on your derived mathematical model.

After going through the stages of problem solving with the use of multiple representations, the student should be able to use the mathematical model to find the value of an unknown quantity or quantities.

2.2.2.d Interview Problems

The interview problems were selected after an initial examination of the students' problem solving work on the 14 homework problems has conducted. In the interviews, the "Blowgun" problem was given first and the "Skier" problem last. Like the homework problems, these problems are well-defined and require the student to engage in multiple steps to find the unknown physical quantity. Table 3 shows the two problems used in the interviews.

TABLE 3

*The Two Problems Used in the Interviews***Blowgun Problem.** (Uniformly Accelerated Motion)

The length of the barrel of a primitive blowgun is 1.2 m. Upon leaving the barrel, a dart has a speed of 14 m/s. Assuming that the dart is uniformly accelerated, how long does it take for the dart to travel the length of the barrel?

Skier Problem. (Newton's Laws of Motion)

A skier is pulled up a slope at a constant velocity by a tow bar. The slope is inclined at 25.0 with respect to the horizontal. The force applied to the skier by the tow bar is parallel to the slope. The skier's mass is 55.0 kg, and the coefficient of kinetic friction between the skis and the snow is 0.120. Find the magnitude of the force that the tow bar exerts on the skier.

2.2.3 Validity and Reliability

Producing valid and reliable knowledge in an ethical manner is the concern of any research. In this section, I discuss the issues of validity and reliability and explain how these issues were dealt with in this study.

2.2.3.a Internal Validity

The limitations of this study result from the chosen research approach, analysis tools, and the data set. Therefore, if this research is to be meaningful and add to the sum of what we know about students' use of multiple representations in problem solving, then I must explain the methodological issues and limitations of the study. To do this, I will address issues on validity and reliability in this section to establish the trustworthiness of the study.

The most well-known strategy that researchers use in order to promote the internal validity of a study is triangulation (Merriam, 2009). In this study, I used multiple methods and multiple sources of data and then I compared my findings with the literature on problem-solving research. Figure 3 shows the triangulation concept that I applied in

this study. We can see that in order to answer the research questions that I put forth in the beginning of the study, I attempted to view the findings from multiple points of reference.

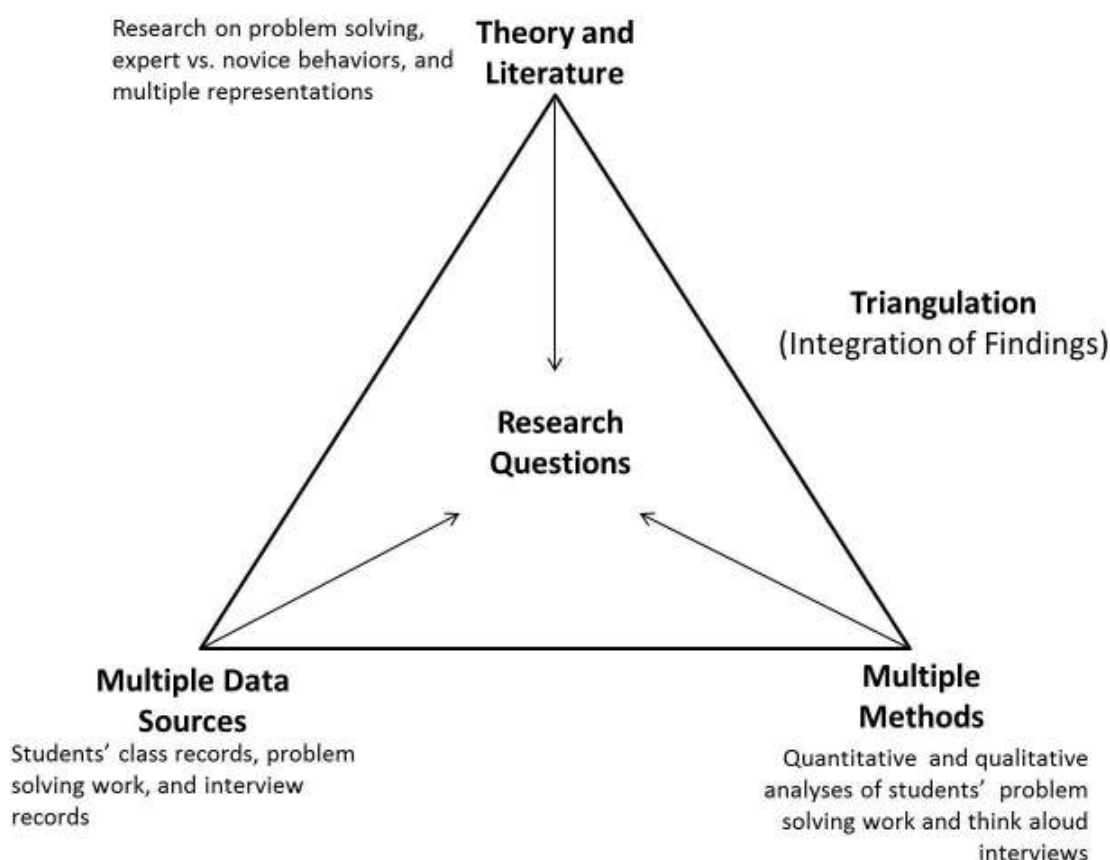


FIGURE 3. Triangulation. The figure shows the concept of triangulation applied in this study to establish internal validity.

Another validation strategy that I used in this study is prolonged engagement and persistent observation in the field (Creswell, 2013). I learned the high school physics curriculum for more than a year through class observations and maintained regular correspondence with the high school physics instructor about the conceptualization and implementation of the research. I was also regularly present in two class sessions per

week from the beginning to the conclusion of the two phases of data collection in order to build trust and long-term contact with the participants of the study.

In one of the previous sections, I have included a clarification of researcher bias as a validation strategy. This strategy is sometimes labeled researcher's position (Merriam, 2009). I articulated and clarified my experiences and theoretical orientation to the study to allow the reader to better understand possible influences in my interpretation of the data. Another validation strategy that is built into this thesis project is the process of peer review (Merriam, 2009). The study had to pass through a faculty committee for comments on the design in prior to the implementation and comments of the findings upon its completion.

2.2.3.b Reliability

For this research to be reliable, it is important to carefully document the data collection and analysis procedures to make it possible for another researcher, with similar knowledge of the content and context of the research, to replicate the study if needed. This study, however, allows for limited replication since a sample of convenience was used and the participants in the interviews have unique characteristics that may not have been completely described in this study due to the limitations inherent to the research instruments. Because each physics course has unique features, such as the teacher, textbook, and student population, precise replication is not possible. It is more important and practical to build upon this study rather than to replicate it since this is an exploratory research. In one of the previous sections, I have discussed how the findings of this study

might be used in designing a quantitative or qualitative study that would lead to definitive results or findings.

2.2.3.c External Validity

The high school teacher in this study used a Modeling Instruction curriculum for physics. This means that the population of students in this study is exposed to a representation-rich learning environment. Because the course uses a particular pedagogy that may not be the preferred program of instruction in other schools, the results of this study are not transferable to traditional courses in which students are not exposed to activities that put emphasis on the use of multiple representations. More scaffolding supports based on the results of PER are needed to address the challenges in traditional physics classrooms.

The external validity of this study therefore depends on applying it to a similar context and content. Are the results transferable to other honors, algebra-based, high school physics courses, with similar curriculum? Since a sample of convenience was used in this study it would be better to think in terms of translating the results to a comparable situation rather than generalizing the findings to the same context and content (Lincoln & Guba, 1985). To make transferability possible, I aimed to provide sufficient descriptive data of the students' background and problem-solving work.

2.2.4 Analysis Methods

2.2.4.a Data: Homework

A large data set was accumulated in this study and as a result, I was selective in my presentation by choosing subsets that are descriptive and concise. For instance, in the

examination of the effect of the use of problem solving tasks on the students' use of representations, I presented information from the aggregate data and then I pulled the data apart by selecting data from a specific problem and drew meaning from the information that was not apparent from the examination of the data set as a whole. Figure 4 shows how I advanced in analyzing the data set from the 14 problems given to the students during the first phase of data collection.

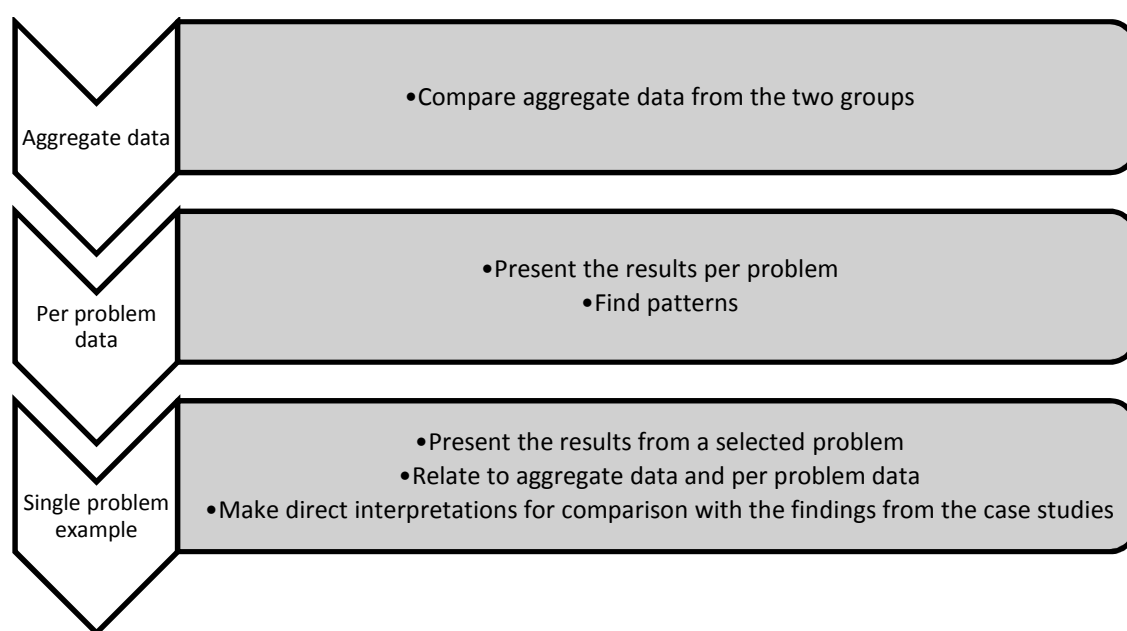


FIGURE 4. Analysis Method for the Homework Data. This figure shows the analysis procedure for the data gathered from the 14 study problems given to the students in the two groups.

To illustrate the advantage of analyzing the data in different levels, I invite the reader to consider the research question pertaining to the effects of using the problem solving tasks. One of the first things that we would want to know would be which of the two groups performed better. Which group has the higher average problem solving score in general? To answer this question, we would have to look at the aggregate data.

The information from the aggregate data, however, is limited, and there might be differences between the two groups that we may overlook if we don't pull apart the data. For instance, if there was no difference in problem solving performance it would not necessarily mean that there was no difference in the use of representations. Presenting the results per problem would allow us to find patterns and trends. If the two groups were found to have relatively the same average problem solving score, then it would mean that if we examine the results per problem, we would see that in some problems the SG students performed better than the CG students and in other problems CG students performed better than SG students, or in all problems both groups had relatively equal problem solving scores leading to the result that we have seen in our inspection of the aggregate data. We can then examine if we would be able to observe the same results if we look at the use of representations of each group per problem. We can be more confident in saying that the scaffolding resulted to more students drawing visual representations if this is the trend in most of the problems, or at best, in all of the problems.

Finally, analyzing the results for one problem allows us to examine special cases and look into details that are not apparent from the first two levels of analysis. A problem in which students generated different diagrams that can be categorized in some way is more valuable to interpret compared to a problem where the students had the same output or problem solving score. I summarized my findings from my analysis of the data from different levels and to serve as a source of information in my analysis of the data from the cognitive interviews.

To address the research questions, the solutions to homework problems (and interview problems as well) were scored based on the rubric shown in Table 4. The score of the students will be used as a measure of performance on problem solving.

TABLE 4

Rubric for Scoring Students' Problem-solving Work

0 NO WORK	1 INCORRECT	2 INADEQUATE	3 COMPLETE
No evidence of problem solving work	The solution reflects that the student was unable to identify the key concept(s) needed to proceed from one step to the next; typically shows plug-and-chug work	The solution reflects that the student was able to identify some key concept(s) and was able to come up with a somewhat organized solution; typically shows success in choosing equations and reveals misconceptions that lead to an incorrect answer	The solution reflects that the student was able to identify the key concept(s) needed to proceed from one step to the next; typically shows organized work and an understanding of the problem

Similarly, the representations used by the students should be identified and coded for data analysis. Table 5 shows the specific representations defined in this study for comparison purposes.

TABLE 5

Categories of Student-generated Representations

Representations	Description and Examples
Diagram	Drawing or alteration of a picture or a schematic diagram (e.g., drawing of a box of mass m pushed by a worker)
Written Explanations	Sentences or phrases expressing an idea or physics concept; explanation of problem-solving approach (e.g., “When a projectile reaches maximum height, the vertical component of its velocity is momentarily zero.”)
Math, Symbolic	Equation(s) or derivation of mathematical model (e.g., “ $\Sigma \mathbf{F}_x = -\mathbf{F}_{g(x)} - \mathbf{F}_{k(x)} + \mathbf{F}_a = 0$ ”)
Math, Numerical	Numerical expressions (e.g., “ $227 + 58 = 285$ ”)

2.2.4.a Data: Cognitive Interviews

There were two groups in this study: the scaffolding group and the comparison group. To provide “depth” to my analysis of the interviews, I used multiple sources of information. In this study, the sources of information are the problem solving solutions of the students from the two groups for 14 physics problems, the responses to the checklist of problem solving tasks, verbatim transcripts of the interviews, observations of the audio-video files, and student background information gathered from surveys (i.e., SIS, FCI, MPEX) and instructor’s class records.

To analyze the data, I began by transcribing the interviews. I used two types of descriptions, one is a narrative description and the other is a pictorial description to supplement the narrative descriptions and provide a quick and easy sense of the students’

problem solving activities. In this study, I refer to the pictorial descriptions as problem solving path diagrams. For example, in one of the interviews, a student explained a part of his solution where he got stuck and he mentioned that once he figured out what he needed to do, there was a clear path. I wanted to map the path for each student for easier comparisons. The problem solving path diagrams show the process of problem solving for each of the students. I used my findings from Phase 1 data to guide my analysis of Phase 2 data by finding examples of students' problem solving behaviors that could be related to the findings from the homework data.

CHAPTER 3

FINDINGS

This chapter presents the results of the surveys administered to the students, aggregate data from the homework problems and descriptions of the cognitive interviews with the students. Results from the homework data were compared with the findings from the interviews.

3.1 Data: Participants

The Student Information Sheet (SIS), Force Concept Inventory (FCI) and Maryland Physics Expectations Survey (MPEX) were administered to the two groups to describe the participants in terms of background variables, physics knowledge, and attitudes toward the subject. Table 3 summarizes the responses of the students on each of the items in the SIS survey.

TABLE 6

Students' Responses to SIS Items

Question	Scaffolding Group, % n = 23	Comparison Group, % n = 20
How well prepared do you feel to deal with the subject matter of physics?		
Unprepared/Somewhat prepared	61	50
Prepared/Very well prepared	39	50
What was the last math course you completed?		
Pre-Calculus/Algebra/Trigonometry	35	70
Calculus	65	30

When did you take your most recently completed math course?		
Last semester	78	75
Two semesters ago or more	22	25
Are you enrolled in a math course this semester?		
No	91	90
Yes	9	10
What grade do you expect to receive in this course?		
A (90-100)	87	85
B (80-84.9) or B+ (85-89.9)	13	15
Approximately how much time per week do you anticipate spending on this course in addition to regular class sessions?		
Less than 5 hours per week	13	30
5-9 hours per week	61	55
10-14 hours per week	26	15

In terms of feeling of preparedness, majority (57%) of the SG students reported that they were “somewhat prepared” while half (50%) of the CG students said that they were “prepared” to deal with the subject. In both groups, one student reported feeling “unprepared”. There were two (9%) SG students who said that they were “very well prepared.”

The modeling physics course is algebra-based and all the students in both groups have taken the pre-requisite math courses. Majority (65%) of the SG students have previously taken calculus while majority (60%) of the CG students have recently completed a pre-calculus course. Among SG students, there was one (4%) whose last math course taken was trigonometry and among CG students, there were two (10%) who have recently completed algebra. In both groups, majority of the students have taken their most recently completed math course in the previous semester. Also, majority of the

students from both groups were not enrolled in a math course in the same semester when this study was conducted. Table 6 also shows that majority of the students from both groups expected to get a grade of A in the physics course and that they anticipated spending 5 to 9 hours of study time per week in addition to the time for regular class sessions.

In Table 7, we are shown the results of the MPEX survey administered to both groups. The results are presented by specifying the percentage of favorable responses.

TABLE 7

Percentage of Students' Favorable and Unfavorable Responses to the MPEX Survey

Response	Scaffolding Group n = 23	Control Group n = 20
Favorable % (SD)	49 (3.30)	46 (3.97)
Unfavorable % (SD)	29 (3.27)	26 (3.56)

A guide on how to use the MPEX is provided by the University of Maryland Physics Education Research Group on their website. A “favorable” response is defined as a response in agreement with the expert response (Appendix E) and an “unfavorable” response is defined as a response in disagreement with the expert response. “Agree” and “strongly agree” responses (4 and 5) were added together. Similarly, “disagree” and “strongly disagree” responses (1 and 2) were also combined. Subtracting the sum of the favorable and unfavorable responses from 100 gives the percentage of “neutral response” and “no answer.”

FCI pre- and post-test scores were also obtained for comparison purposes. Table 8 shows the average scores and standard deviations given in percent. The FCI post-test was taken by 19 SG students and 18 CG students.

TABLE 8

FCI Pre- and Post-test Scores

	Pre-test % (SD)	Post-test % (SD)
Scaffolding Group, n = 23	25 (2.11)	77 (2.77)
Comparison Group, n = 20	23 (1.79)	74 (2.88)

Hake (1996) has documented FCI data for over six thousand high school and college students. Hake's data show that in reform courses using non-traditional teaching methods, high school students average about 65% on the FCI posttest while the average FCI posttest score for students in a modeling physics course was 74%. The national average FCI post-test score in traditional classes is about 48%. Table 5 shows that the pre-test scores of both groups are slightly above the random guessing level of 20%. In the post-test, the students from both groups scored above the threshold for understanding Newtonian mechanics which is 60%. Also, their average score is comparable to the national average for modeling physics courses.

In this section, I have described the two groups involved in this study. Data from the SIS, MPEX, and FCI was presented in summary tables so that the reader can easily compare the two groups. I have treated the groups to be equivalent and I did not apply any statistical test since I did not attempt to generalize beyond the students in the convenience sample. For optimal comparison results in future research work, quasi-

experimental or experimental designs would allow researchers to use statistically equivalent groups.

3.2 Data: Homework

3.2.1 Problem Solving Performance

Fourteen (14) homework problems in mechanics were given to the students in the first phase of data gathering. The key physics concepts needed to solve each problem are shown in Table 9. The sequence of the problems is based on the arrangement of topics in the syllabus of the course.

TABLE 9

Key Physics Concepts on the 14 Homework Problems

Topic	Problem	Key Physics Concepts
Kinematics	1 Lake	Distance, displacement
	2 Earth	Average speed, average velocity
	3 Jetliner	Average acceleration
	4 Blowgun	Uniformly accelerated motion
	5 Astronaut	Uniformly accelerated motion
	6 Two Players	Uniformly accelerated motion
Dynamics	7 Box	Application of Newton's first law of motion, Superposition of forces, Static equilibrium
	8 Sign	Application of Newton's first law of motion, Superposition of forces, Static equilibrium
	9 Bricks	Application of Newton's first law of motion, Superposition of forces, Dynamic equilibrium
	10 I-beam	Application of Newton's first law of motion, Superposition of forces, Dynamic equilibrium
	11 Rock	Application of Newton's second law of motion, Superposition of forces
	12 Black Belt	Application of Newton's second law of

	motion, Average acceleration
13 Rocket	Application of Newton's second and third laws of motion, Apparent weight
14 Baseball	Application of Newton's second law of motion, Frictional force

Table 10 shows the mean score of each group for the 14 homework problems.

In general, the performance of both groups in the homework problems, by looking at the aggregate data, is relatively equivalent. However, if we look at the performance of each group per problem, the mean score per problem of the scaffolding group was higher in 9 out of 14 (64%) problems (Refer to Figure 4).

TABLE 10

Students' Performance on the 14 Homework Problems

	Mean	Standard Deviation
Scaffolding Group	18.0	2.35
Comparison Group	18.4	2.54

The highest possible score per problem is 3 (See rubric on page 40). SG, n = 19; CG, n = 20.

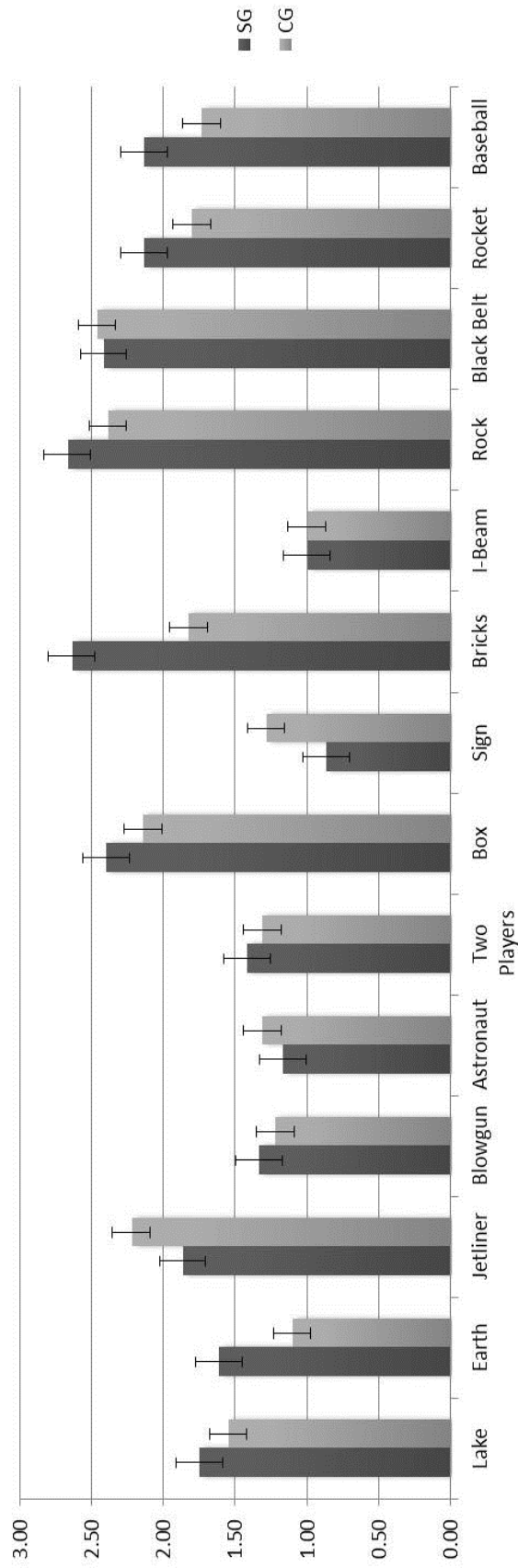


FIGURE 5. Students' performance on the 14 homework problems. The figure shows the mean score of the groups per problem. The problems are arranged chronologically (i.e., the "Lake" problem was given in the first week and the "Baseball" problem was given last).

To explore possible explanations to differences in performance, I compared the percentage of students drawing a visual representation per problem. In coding the data, whether a student used visual representations for these two problems, I did not count a drawing if it did not involve any modification by the student. The data show that in 9 out of 14 problems, the percentage of students who used visual representations is at least 20% higher in the scaffolding group. Figure 6 shows the percentage of students in the two groups who drew visual representations per problem.

The results suggest that the scaffolding has resulted in an increase in the use of visual representations. There were three problems – box, sign, bricks – where the percentage of scores by the CG students was relatively high, which means that there are certain types of problem in which students used visual representations without the need for prompts. As seen in the list of study problems in Appendix F, these three problems are about forces. Also, the “Box” and the “Sign” problems have a given picture of the situation described in the problems. In the “Box” problem, 100% of the students from both groups sketched a free-body diagram. The “Sign” problem is the only problem in which more students from CG used visual representations compared to SG. It should also be noted that in this problem, the mean score of the SG is lower than that of CG. The “Sign” problem involves resolving vectors into components and the use of a free-body diagram is necessary for beginning learners. Also, the low mean score of both groups in this problem suggest that it was relatively difficult compared to the rest of the homework problems.

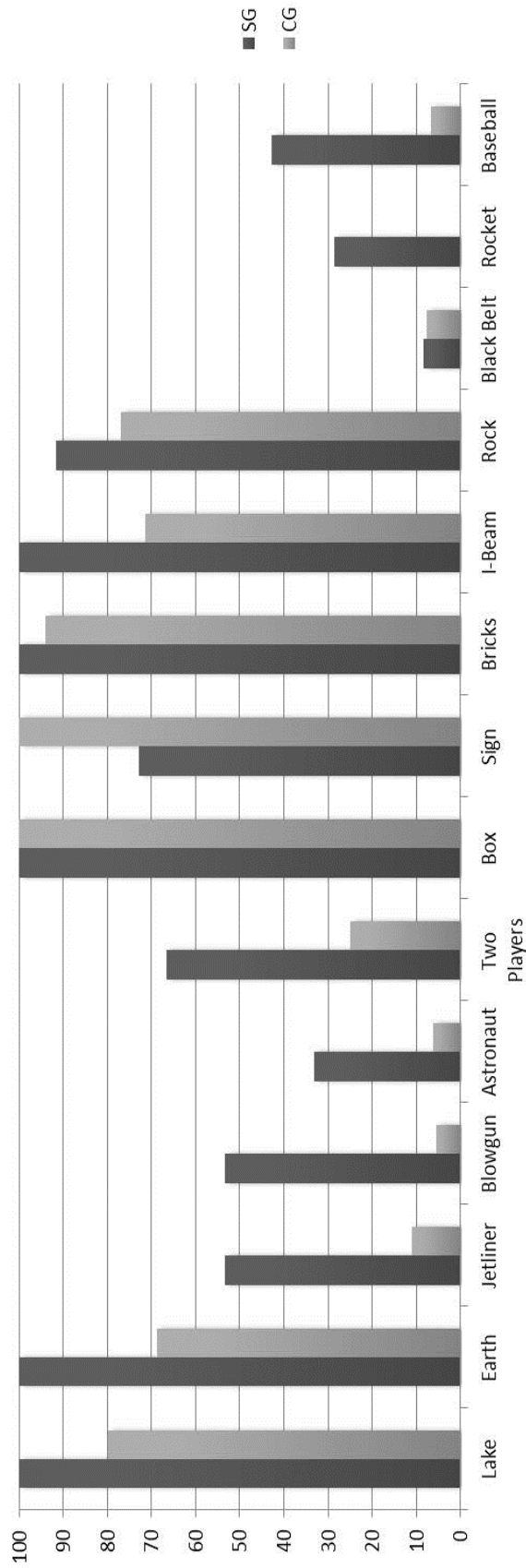


FIGURE 6. Use of visual representations. The figure shows the percentage of students who used visual representations on the 14 study problems.

In Figure 5, the mean scores of the CG in the “Jetliner” and “Astronaut” problems are higher compared to those of the SG although more students in SG drew visual representations in their problem solving work. In Appendix F, we can find that both of these problems are about one-dimensional motion. This result suggests that there are problems in which visual presentations may not be needed by the students in the process of problem solving or the use of other representations such as mathematical expressions were found to be sufficient by the students to aid them in problem solving. Another example is the result for the “Black Belt” problem where the mean score of both groups is almost the same. In the “Black Belt” problem, more than 90% of the students from both groups did not use any visual representation. The high mean score for both groups suggests that the problem was relatively easy compared to the rest of the homework problems and the students from both groups did not find the need to use visual representations in the process of problem solving.

3.2.2 Use of Representations

In the previous section, I presented per-problem data on the use of visual representations. I will explain why I chose to focus on visual representations when the checklist of problem-solving tasks (See Appendix G) was designed to promote the use of multiple representations in problem solving. In an examination of the results per problem, I found a notable increase on the use of visual representations (Figure 5), but no apparent difference on the use verbal and mathematical representations.

The least used representation by students from both groups was the verbal type. In the checklist given to SG students, two reasoning tasks were included to influence the students to use verbal descriptions and explanations, but there was no noticeable increase in the use of verbal representation compared to CG students. This result implies that the scaffolding was ineffective in influencing students to verbally express their reasoning in problem-solving. It should be noted, however, that the absence of verbal representation in the students' problem solving work does not automatically indicate weak reasoning in problem solving. Reasoning can be demonstrated with the use of other representations although findings from the interview data revealed that conceptual reasoning is not central to the problem-solving process of the students.

To further demonstrate how the scaffolding affected the students' use of representations, I will present the results from the "Lake" problem (Figure 7). I chose this problem because the problem solving scores of both groups have a broad range, which implies that it was of average difficulty for the students. The data from this problem would also allow us to examine the use of representations of students with different problem solving performance.

Lake Problem

One afternoon, a couple walks three-fourths of the way around a circular lake, the radius of which is 1.50 km. They start at the west side of the lake and head due south at the beginning of their walk. (a) What is the distance they travel? (b) What are the magnitude and direction (relative to due east) of the couple's displacement?

FIGURE 7. Text of the "Lake" problem.

In applying the rubric (See page 37) to score the students' work in the "Lake" problem, student responses without any written problem solving work were given a score

of 0. It should be noted that there is a possibility of undercounting in evaluating whether a student engaged in problem solving. Thus, a score of 0 does not mean that the student did not write anything on a homework sheet. For instance, the student may have written down the given values in the problem, but did not proceed to solve it for unknown reasons. Thus, a score of 0 means insufficient evidence to establish that the student worked on a given problem. A score of 1 (Incorrect) usually reflects undirected, trial-and-error work. A score of 2 (Incomplete) was given when the student was able to find the distance, but not the displacement. Finally, a score of 3 (Complete) was given to students who were able to find both the distance and displacement. Figure 8 shows a sample solution to the “Lake” problem with a score of 3.

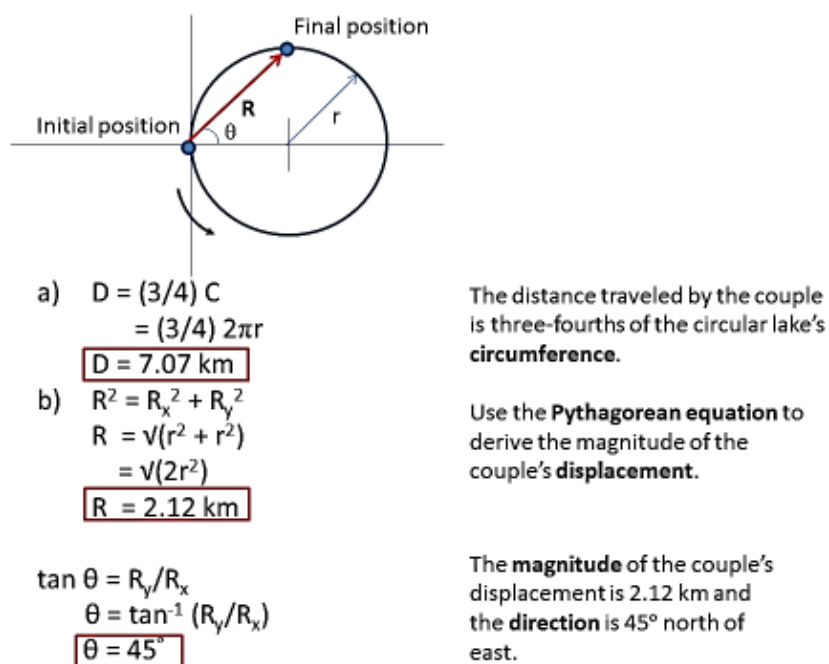


FIGURE 8. Sample solution to the “Lake” problem. The figure shows a solution with a score of 3 (Complete) based on the rubric.

Figure 9 shows the students' performance in the "Lake" problem based on the scoring system that I have described.

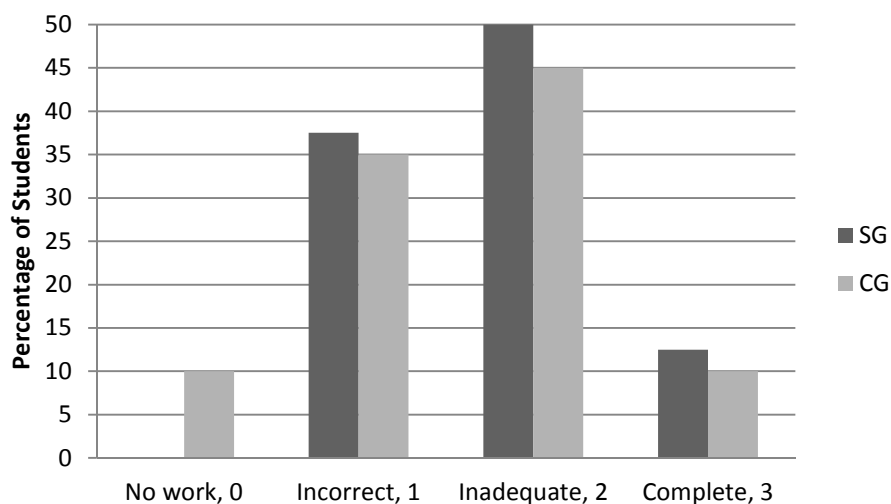


FIGURE 9. Distribution of students' scores on the "Lake" problem. The figure shows a comparison of the percentage of students grouped by scores.

In Figure 9, we can see that the "Lake" problem is of average difficulty with the majority of the students receiving a score 2 or being able to find the distance, but not the displacement. It should be noted that none of the SG students received a score of 0. It would seem that the scaffolding helped some students to find a starting point in solving the problem by attempting to draw a visual representation and identifying equations that may be used in formulating a solution

Figure 5 showed the comparison of the performance of both groups in the "Lake" problem. We have already seen in the previous section that in this problem, more students from SG used visual representations than CG students (See Figure 6). In the next sections, we will examine the other representations used by the students. Figure 10 shows

the percentage of students from both groups who used various representations in solving the “Lake” problem.

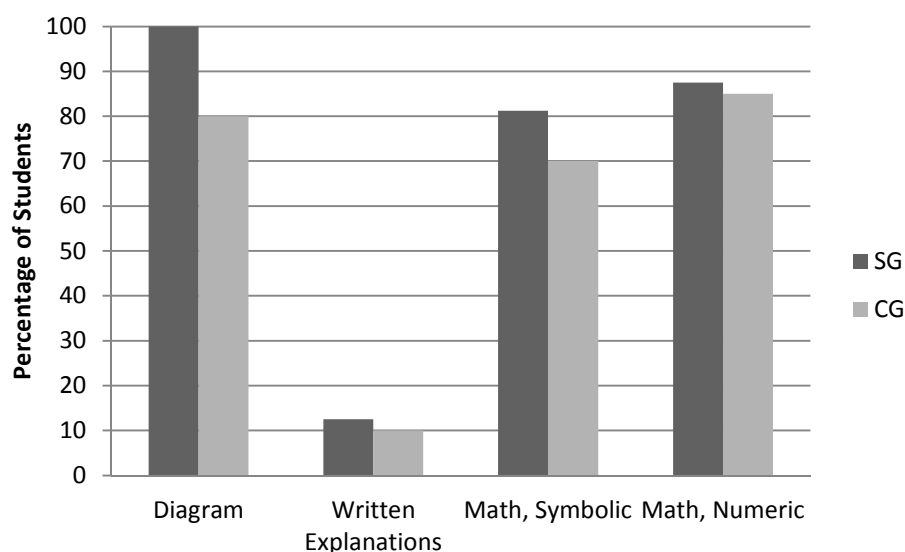


FIGURE 10. Use of representations in the “Lake” problem. The graph shows that majority of the students from both groups used a combination of visual and mathematical representations in problem solving.

The results shown in Figure 9 suggest that while students in SG accomplished the first two tasks in the checklist, which was to use a virtual representation, very few of them did what was asked in the reasoning tasks. The use of mathematical representations, as we would expect, is common in both groups since problem solving in introductory physics is usually associated with the use of mathematical tools as shown by the type of problems that can be seen in textbooks. The result from the “Lake” problem and the other study problems show that students rarely provide written descriptions and explanations in their problem solving work.

I also examined how the students responded to the items in the checklist in order to see if their evaluation of their own work is consistent with their problem-solving

output. The checklist has 2 tasks for every representation. Figure 10 shows the percentage of SG students' who accomplished the checklist items.

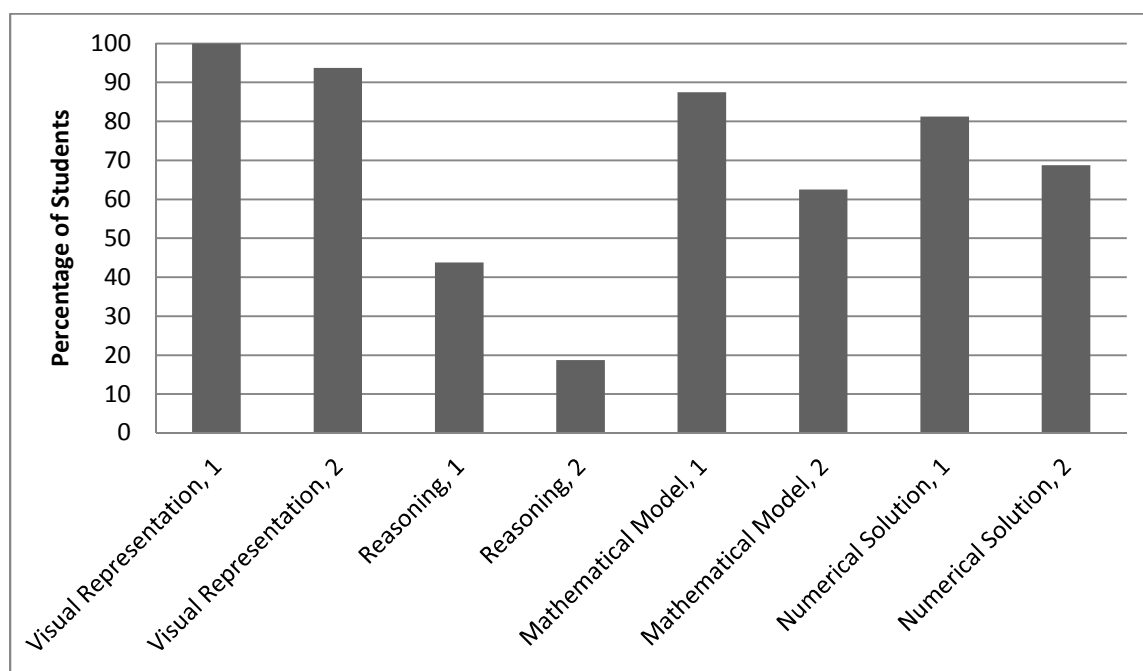


FIGURE 11. Responses on the checklist of problem solving tasks for the “Lake” problem. The graph shows the percentage of SG students' who reported that they have accomplished an item in the checklist of problem-solving tasks (Appendix G).

From Figure 11, we can see that the students' responses closely resemble the trend that can be observed in Figure 10. Students do not typically write down the physics concepts they use in their problem solving work and even when they were explicitly asked to do so, very few of them did. We should notice, however, that nearly half (44 %) of the SG students reported that they identified the key concept(s) needed in solving the problem. Although this is relatively low since identifying concepts should be central to the process of solving physics problems, we can deduce that students must be using other forms of representations to express their reasoning aside from verbal descriptions and explanations that were asked for in the checklist of problem solving tasks.

3.2.3 Quality of Student-generated Representations

We can use the problem solving scores to identify how representations used might relate to the performance of the students. For instance, if all students have generated a diagram for a problem and the problem solving scores are still dispersed, it could mean that the diagrams created by the students must have been different from each other. I continued to examine the results from the “Lake” problem to find out how representations were used by students with different problem solving performance.

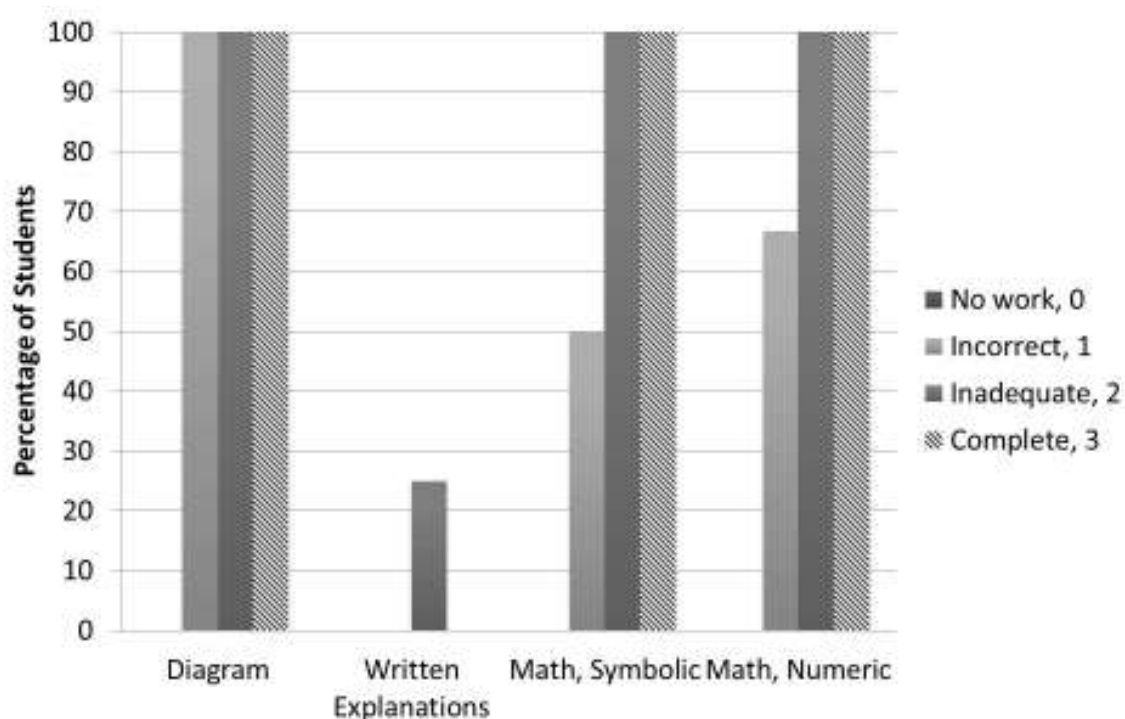


FIGURE 12. Scaffolding group’s use of multiple representations in the “Lake” problem.

Figure 12 shows the percentage of students in the scaffolding group who used specific representations. I calculated the percentages based on the number of students in a group. We can see from the figure that all students who scored a 2 or a 3 in the “Lake” problem used a combination of diagram, symbolic, and numeric math, in their problem-

solving work. This result suggests that the performance of the students may be related to having an integrated set of representations. For instance, in this particular case of the “Lake” problem, the diagram drawn by a student should match the equations that he or she chose in composing a solution. Notice in Figure 11 that although 100% of the students from the bottom group (i.e., students who received a score of 1) drew diagrams, only 50% of them used equations that would correspond to the diagram. Figure 10 also shows that the students who tried to use verbal representations in response to the checklist came from the middle group (i.e., students with a score of 2).

Figure 13 shows the percentage of CG students who used specific representations in groups based on scores.

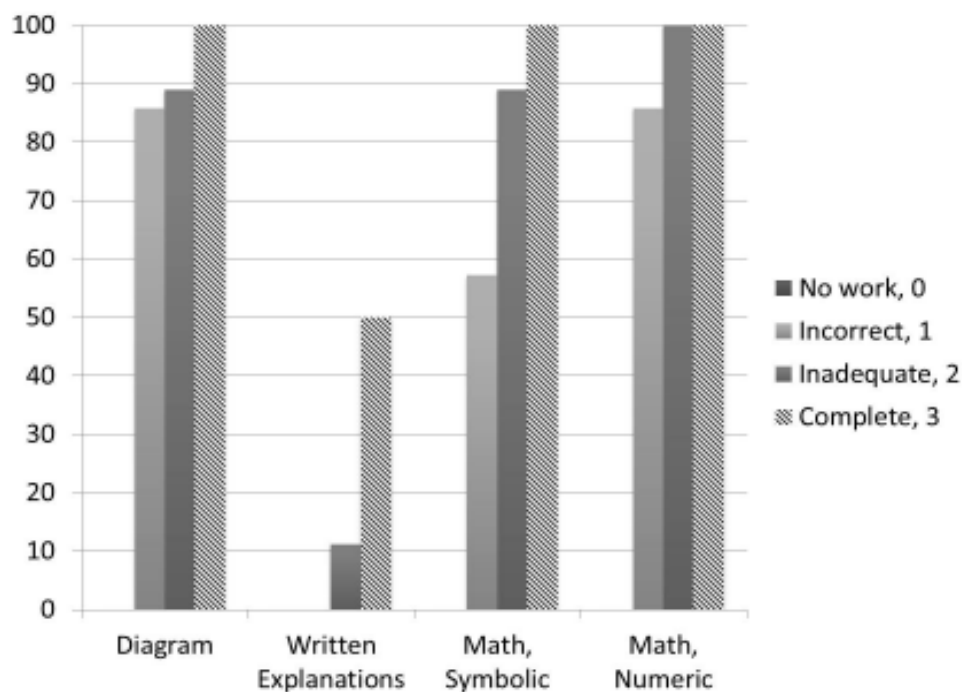


FIGURE 13. Comparison group's use of multiple representations in the “Lake” Problem.

We can see that students from the top group (i.e., students who received a score of 3) were users of multiple representations. The majority of the students from the middle group also used a combination of visual and mathematical representations in their problem solving work. Students from the bottom group were more likely to use diagrams and numerical manipulations. In general, comparing Figure 11 and Figure 12, we see that relatively successful students use multiple representations. However, we also find from the data from both groups that the use of multiple representations does not guarantee success in problem solving. To illustrate this, I have examined the diagrams used by the students and grouped them based on the students' scores. As shown in Table 10, the quality of representations used by the students in both groups can be related to differences in problem solving performance. I sought to verify this observation from my interviews with the students.

TABLE 11

Diagrams Generated by Students for the "Lake" Problem

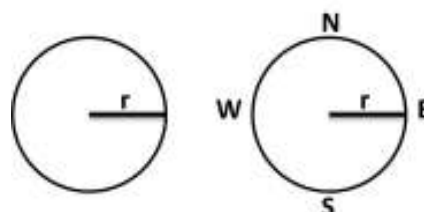
 0 No work

The student may have drawn a diagram and written down given values, but did not proceed

No diagram

 1 Incorrect

The student plugged the given values in an equation



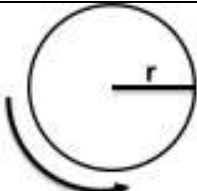
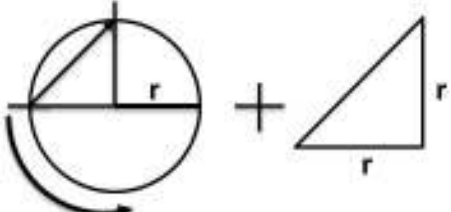
2 Inadequate	
The student knew how to find distance but not displacement	
3 Complete	
The student has a solid grasp of the concepts of distance and displacement	

Table 11 shows that students with different problem solving scores drew diagrams with different features. The concepts of distance and displacement were translated in the diagrams generated by students who scored a 2 or a 3. Students who scored a 1 seemed to have acknowledged only the surface features of the problem and not the underlying concepts needed to solve the problem. Their diagrams contained bits and pieces of information from the problem. Among students who scored a 2 or 3, those who were able to complete a solution drew an additional right triangle to show how they would find the displacement.

3.3 Data: Cognitive Interviews

In this section, I provide examples of in-depth descriptions of the think-aloud interviews conducted with selected students from the two groups. Pseudonyms are used in all the examples. An initial review of the audio-video files of the interviews was done to observe the use of representations and other problem solving behaviors that could be compared to the literature in PER.

3.3.1 Cognitive Interviews

To provide “depth” to my analysis of the effects of the use of problem-solving tasks in guiding students to use multiple representations, I used multiple sources of information. In this study, the sources of information are the problem solving solutions of the students from the two groups for 14 physics problems, the responses to the checklist of problem solving tasks, verbatim transcripts of the interviews, observations of the audio-video files, and student background information gathered from the surveys (i.e., Student Information Sheet, FCI, MPEX).

I began my analysis by creating interview descriptions to present the facts that I have recorded. Table 12 shows the problems used for the interviews.

TABLE 12

Interview Problems

Blowgun Problem. (Uniformly Accelerated Motion)

The length of the barrel of a primitive blowgun is 1.2 m. Upon leaving the barrel, a dart has a speed of 14 m/s. Assuming that the dart is uniformly accelerated, how long does it take for the dart to travel the length of the barrel?

Skier Problem. (Newton’s Laws of Motion)

A skier is pulled up a slope at a constant velocity by a tow bar. The slope is inclined at 25.0° with respect to the horizontal. The force applied to the skier by the tow bar is parallel to the slope. The skier’s mass is 55.0 kg, and the coefficient of kinetic friction between the skis and the snow is 0.120. Find the magnitude of the force that the tow bar exerts on the skier.

The problems are selected from the pool of the end-of-chapter (EOC) problems in the adapted textbook for the high school physics course.

In the next sections, I started by describing the students’ performance overall to show why the student’s problem solving episode was chosen as an example. I also included a diagram showing the order of representations used by the students in solving each problem to provide a quick sense of the problem solving episode. I selected three

examples from each group and included the descriptions of the rest of the cognitive interviews in Appendix I. The 12 students who were interviewed were selected based on their post-FCI scores relative to their class. The post-FCI score is chosen as an indicator of the students' mechanics background after instruction. Table 13 shows the post-FCI scores of the students described in the next section.

TABLE 13

Selected Students for Interview Based on Post-FCI Scores

Post-FCI Score	Scaffolding Group	Comparison Group
Highest	Noah	Joshua
Average	Abby	Anna
Below Average	Cat	Mary

3.3.1.a Cognitive Interviews: Scaffolding Group

Noah

Noah is an example of a consistent user of visual and mathematical representations in solving problems. He had the highest pre- and post- FCI scores in his class and he is relatively successful in problem solving. We can learn from Noah's interview that he uses visual representations to aid his understanding of the problem. We can also see that despite being relatively successful in problem solving compared to the rest of his class, Noah also exhibits novice-like problem solving behaviors such as formula-seeking and exploration of which equation would work for a particular problem.

Blowgun

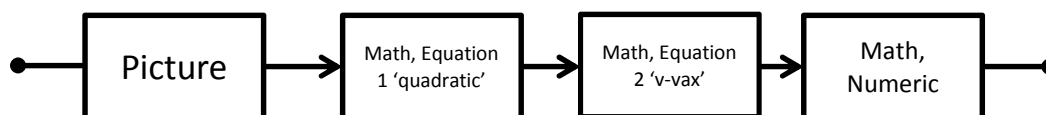


FIGURE 14. Noah's problem solving path for the "Blowgun" problem.

Noel started by drawing a correct picture based on the values given in the problem. In his representation, the dart is leaving the barrel at 14m/s. He continued reading the problem aloud and then he quickly decided on what to do next. "I'm probably going to use the 'quadratic'". He correctly plugged in the values and recognized that he had two unknown variables in the equation: "...we don't know the acceleration and time. We have to figure that out." He set aside his equation with two unknown variables, looked at his equation sheet and mumbled, "What am I going to use?" He said was looking for time and explained that it's been a while since he did a similar problem. He then thought of using 'v-vax'. He quickly worked through the equation and found a value for acceleration which he plugged in to the equation that he has derived earlier from the 'quadratic'. He successfully found the time and did not do any checking. He said he usually does not go back through to check his work but he would think about it for a second and see if it makes sense. He said, "A fifth of a second for a dart to leave a blowgun is pretty reasonable..."

Noah said that he started with the 'quadratic' because that was his favorite equation. He said that it works for a lot of different kinds of problems. He further explained that when he got stuck while working on the problem, he had to look for a different equation that suited his needs more and would only have one variable. When asked about the purpose of his illustration, he said it is a lot easier for him to just look at a

picture instead of just reading a problem since there are instances when he has to read a problem over and over again without really understanding it. He said that a quick picture to look at aids his understanding.

Skier

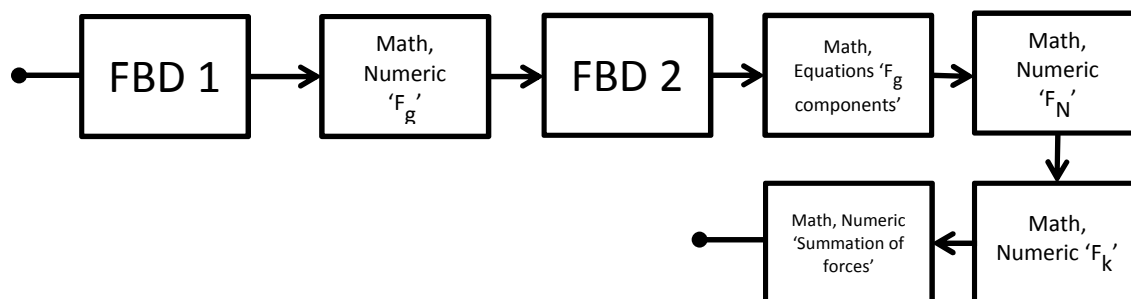


FIGURE 15. Noah's problem solving path for the "Skier" problem.

Noah started by saying that for the skier problem, his diagram would be a force diagram. He drew three forces in his diagram – normal force, gravitational force, and the applied force. He missed drawing the friction force. The direction of his normal force is also incorrect. He calculated the gravitational force and labeled his diagram. He stopped and read the problem again and identified the condition that the skier is moving at a constant velocity. He points to his diagram and said that the force on the +x-axis should equal the force on the -x-axis. He examined his diagram and said that he is trying to find the normal force but he is stuck because of the angle. He then realized that he may have drawn his diagram wrong. He draws a second force diagram with the axes tilted and with the applied force parallel to the +x-axis and the normal force parallel to the +y-axis. Once again he missed drawing the friction vector and his angle was in the wrong place. He proceeded by finding the x- and y- components of the gravitational force and labeled the diagram with his newly calculated values. He had no clear purpose why he needed to

break up the vector. He said, “I usually like to find both of these [the components] just in case I need to find the other one later.” Using the new values he got, he plugged them in to the equation for kinetic friction with the goal of finding the normal force. However, he found a very large number and it made him uncertain. He said, “This doesn’t seem right. I think I messed up somewhere. I think I’ll redo that.” He erases his solution for the normal force and said that he plugged in the wrong values to the equation. He then said that he forgot that he could just move up the value of the y-component of the gravitational force as the normal force. He used the equation for kinetic friction once again and said that it will give him the value of the applied force. He examined his solution and realized that what he has calculated was the kinetic friction force. He then added the x-component of gravity to the friction force and he said that the sum is the force that the tow bar exerts on the skier. He said that he knew that the forces are equal because the skier is pulled uphill at constant velocity.

In the interview with Noah, he said that he always starts with force diagrams in solving problems involving forces. When he gets stuck, he said that he usually looks for a different formula or goes back to check if there was something wrong with his solution. When he accomplished the checklist, he said that he just used formulas and was not sure about key physics concepts that are relevant to the problem so he did not really identify anything. He said he was not entirely confident with his solution in the skier problem but he expressed that he was more confident with his solution to the blowgun problem.

Abby

Abby is an example of an inconsistent user of visual representations with mixed success in problem-solving. Abby's pre- and post-FCI scores are around the class average. We learn from Abby's interview that she would directly proceed on finding an equation instead of using representations to qualitatively describe a problem if she thinks that the problem is simple based on an assessment of the problem's surface features.

Blowgun

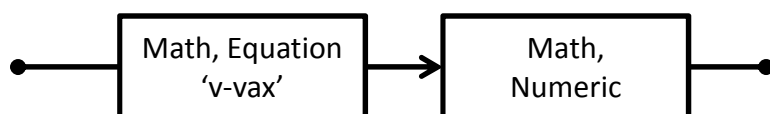


FIGURE 16. Abby's problem solving path for the "Blowgun" problem.

After reading the problem, Abby looked at her equation sheet and said "I'm going to use the 'v-vax' formula. She quickly wrote down the equation with certainty and plugged in the given values. She plugged in 14m/s as the value for the initial velocity and 0 for the final velocity. She was able to calculate a negative value for acceleration. She declared that as her final answer.

When asked to explain her solution, Abby said that based on the given values, she knew that she could find the acceleration using 'v-vax'. She also said that "upon leaving the barrel" meant initial velocity and the final velocity was zero because that was "when it's [the motion] over". Her explanation revealed that she did not analyze the situation in terms of concepts but directly translated common verbal cues to numbers without providing any explanation. She did not realize that she was supposed to look for the time it takes for the dart to travel the length of the barrel.

Abby said that she was confident with her solution. When asked if there was a way for her to check if her answer was correct she said, “I don’t know...Just like if it would make sense in the problem I guess. Since a gun is fairly fast I would expect it [the acceleration] to be fairly high. And since it’s slowing down out of the gun, it would be negative.” When asked why she did not draw a diagram, she said that she does not need diagrams for fairly easy problems so it just depends on what kind of problem it is.

Skier

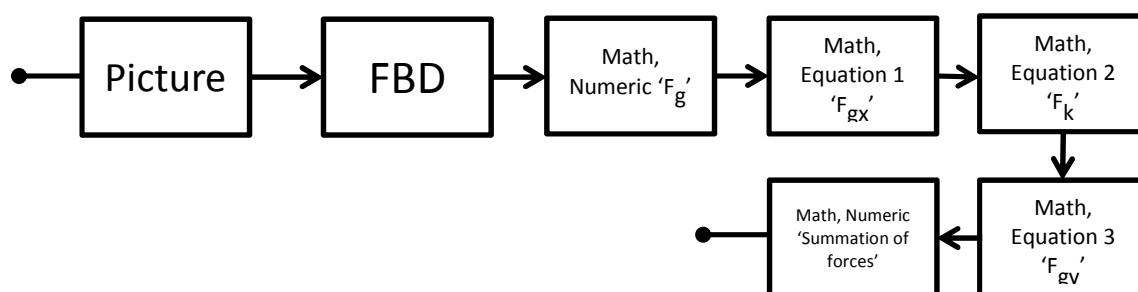


FIGURE 17. Abby's problem solving path for the "Skier" problem.

Abby started by drawing a picture and writing down the given values. (In the interview after she had solved the problem, she said, “I made kind of a visual representation of the slope.”) She then drew a force diagram and correctly identified all of the forces acting on the skier. She calculated the gravitational force and labeled her force diagram. She stopped and examined her diagram and identified what was asked for in the problem, which was the force applied by the tow bar. She looked at her equation sheet and then she voiced out her plans on how to find the values she needed. For instance, she said, “We need to find this y-vector from gravity in order to find the normal force.” She then went on to find the kinetic friction force. She said that it would be equal to the applied force since they were opposite of each other. After calculating the kinetic

friction force, she said that it was her final answer but then she quickly took it back after looking at her diagram. She realized that there was a component that she missed to include in her calculation of the sum of all forces. She said, “Oh no! That would not be the answer. Since we also have a...”x”. We have an x-vector from the gravity so we have to add those two [F_{gx} and F_k] together. She quickly solved the rest of the problem and arrived at the correct answer.

In the interview after she had solved the problem, Abby said, “I just try to think reasonably in a real life situation like how it would work because when I got this [F_k] the first time, it seemed really low, so I just felt like something was off so I had to go back and check.” She said that her way of checking would be to work backwards. When she accomplished the checklist of problem solving tasks, she explained why she drew a diagram: “Just to kind of like get the, I don’t know, the incline in my head, because sometimes that can be a little tricky.” Abby said that she was pretty confident with both of her solutions for the interview problems.

Cat

Cat is an example of a consistent user of visual and mathematical representations but was unsuccessful in solving both the interview problems correctly. Her pre- and post-FCI scores are below the class average. We learn from her interview that she sometimes generate visual representations that do not provide useful information in problem solving because they reflect only the surface features of the problem and not the underlying physics concepts.

Blowgun

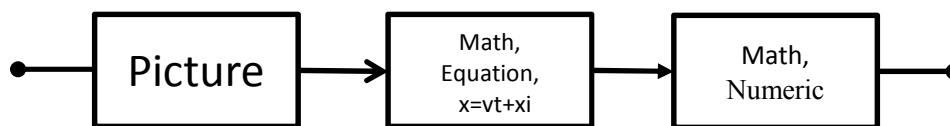


FIGURE 18. Cat's problem solving path for the "Blowgun" problem.

After reading the problem, Cat said she would first draw a picture because visuals help. She drew a picture of a gun and wrote down the length of the gun's barrel and the velocity of the dart. She did not identify whether the velocity was the dart's initial velocity or final velocity. She read the problem again and then she looked at her equation sheet. She used an equation that is valid only for motion at constant velocity. She copied the equation and then she plugged in the values. She simply divided 1.2m by 14m/s to get a value for time. Her final answer was 0.0857 s. She said that to check if her answer is correct, she could work back into the equation or use a different equation. She also said that she does not normally check her answers and that maybe she should.

Skier

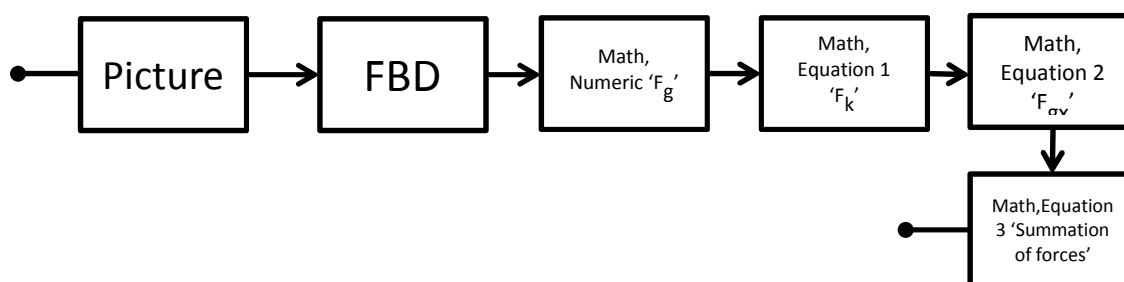


FIGURE 19. Cat's problem-solving path for the "Skier" problem.

Cat read the problem and then she started drawing a picture and labeled it with the available information. When she was about to draw the vector for the force applied on the skier, she decided to draw a free-body diagram instead. She was able to identify all the

forces acting on the skier but she drew the normal force in the wrong direction. She said that the normal force would be the same as gravity. She used trigonometry to find the components of the gravitational force vector and then wrote down a correct mathematical expression for the sum of all forces along the x-axis. She plugged in the values that she had calculated to her equation and then she solved for the force exerted by the tow bar on the skier.

In the interview, Cat said that drawing a force diagram helps. She said that she does not mostly think about concepts so she does not write them down and it is easier for her to draw a picture. Although she wrote down a correct mathematical expression for the sum of all forces along the x-axis, she did not relate her equation to the problem description that the skier is moving at constant velocity. She said, “We did the sum of x-components which equals zero since they equal, then I just set that up to prove that those are equal and then I just plugged what I knew in the equation...”

When asked about what she does when she gets stuck in problem-solving, she said, “...I go back and see if I missed anything in the problem, if I like misread the problem or I go back to the force diagram and see if I missed anything there.” To check if her answer is correct, Cat said that she could re-check her work but she doesn’t know how to plug in to different equations so she just examines if her labels are right. She said that she is more confident with her solution to the second problem since the first problem seemed to be simple and maybe she missed something. Finally, she said that if she used the right equations, both of her answers should be correct.

3.3.1.b Cognitive Interviews: Comparison Group

Joshua

Joshua is a consistent user of visual and mathematical representations and is relatively successful in problem-solving. He had the highest pre- and post-FCI scores in his class. We learn from the interview that Joshua uses visual representations to aid his understanding of the problem. Despite being relatively successful in problem-solving, Joshua also engages in formula-seeking until he gains an understanding of how to proceed.

Blowgun

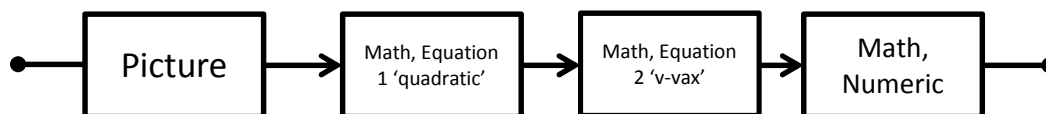


FIGURE 20. Joshua's problem solving path for the "Blowgun" problem.

Joshua read the problem and drew a picture. He labeled his picture with the information given in the problem. He said that the dart leaving the blowgun is traveling at 14m/s and then he identified that he needs to find how long it takes for the dart to travel the length of the barrel. He said that he needed something with distance and velocity and decided that he would start with the 'quadratic'. He wrote down the equation and plugged in the values he had and noticed that the acceleration was missing. "This isn't right," he said, "I'm trying to figure out if this is the right equation because my brain is telling me right now that this is for falling bodies." He reasoned that since the problem described the dart's motion as uniformly accelerated, there was acceleration from 0 to 14m/s.

Joshua looked at his equation sheet then he wrote down the given values again and he identified the values that he needs. Joshua realized that he needs to find the

acceleration of the dart before he could find the unknown time of travel. He said he would try to find the acceleration by using ‘v-vax’ first then he would come back to the ‘quadratic’. After finding the acceleration, Joshua said, “That just seems that it’s gone way too fast but it makes sense. I’m gonna run through it again, sort of, in my head.” He checked his calculation and then he plugged in the value of the acceleration to the ‘quadratic’. He used dimensional analysis to check the units and then he wrote down his final answer.

In the interview, Joshua said that he started with the ‘quadratic’ because he was thinking of falling bodies whose acceleration would be $9.8[\text{m/s}^2]$ but then he realized that was not the case for the given problem. When he got stuck, he said he had to go back to his formula sheet and see if there’s something else that might work better. He also explained that he drew a picture because it helps him if he can visualize something. He said that he can check if his answer is right by plugging the value back to the equation.

Skier

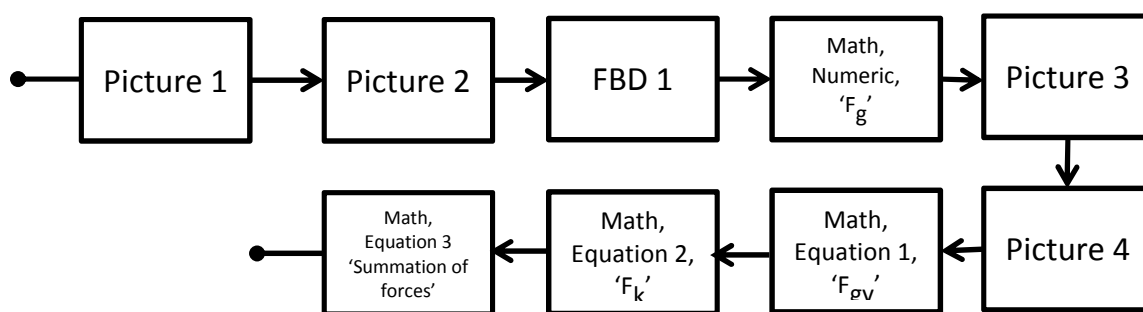


FIGURE 21. Joshua’s problem solving path for the “Skier” problem.

After reading the problem, Joshua drew a picture and wrote down the information he could get from the problem. He identified the target variable and then he briefly looked at his notes. He said that his diagram is not giving him all the information he

wanted at the moment so he would draw a force diagram. He was able to identify all the forces acting on the skier but he had difficulties with identifying where to put the angle in the free-body diagram. He drew another diagram and he used his pencil to help him visualize the rotation of axes. He was still unhappy with his diagram but he decided to find what he can from what was given to him. He calculated the gravitational force and then he said he can use that to find the normal force which would allow him to solve for the kinetic friction force. He then drew a picture of a triangle to solve for vector components. He stopped and looked at his equation sheet. He said he is looking for how to solve for the normal force and added that he knew it had something to do with the sum of forces. He examined his diagram and said that the normal force has to be less than the gravitational force and then he finally went back to one of the free-body diagrams that he drew and said, “Normal force, here we are. That’s the triangle I’m looking for right here.”

He drew another diagram to solve for vector components. He was not satisfied with the first value he calculated for the normal force and said that “it seems awfully low” so he tried using cosine instead and he was happy with the outcome: “That seems more right.” After finding the normal force, he calculated for the frictional force as planned and then he equated the frictional force to the force applied by the tow bar on the skier. He checked his worked and after a while, he said that was his final answer.

In the interview, Joshua explained that he stumbled around the force diagram because “it’s been a while”. He said he was sure about the direction of the force but for

the magnitude, he could plug some of his numbers back to check. Joshua said that he was confident with both of his answers.

Anna

Anna is an inconsistent user of visual representations with mixed success in problem-solving. Her pre- and post-FCI scores are around the class average. We learn from the interview that Anna does not draw diagrams for problems that can be solved by selecting equations but she would always start with a free-body diagram when working on force problems.

Blowgun

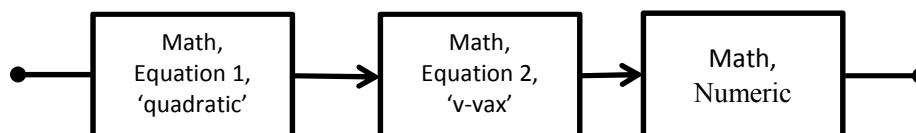


FIGURE 22. Anna's problem solving path for the "Blowgun" problem.

Anna read the problem and then she looked at her equation sheet. She said she would use the 'quadratic' because it had the displacement and time. She copied the equation and plugged in values then she noticed that she did not have the value for the dart's acceleration. She looked at her equation sheet again and said, "Oh wait. First, I'll use 'v-vat' to find the time. I'll go with it." She thought about it for a while and then she changed her mind. She said she would use 'v-vax' to find the acceleration. She copied the equation and plugged in values. She mistakenly identified 14m/s as the initial velocity of the dart. She was able to calculate a value for acceleration which was supposed to be negative but she discarded the sign. She looked at her equation sheet again and then she

plugged in her calculated value for acceleration to the ‘quadratic’. She picked the positive value for time. She explained that time can’t be negative.

In the interview after she had solved the problem, Anna said that she usually starts solving a problem by writing down an equation that involves all the variables and from there figure out which variable she needs to find before moving on to another equation. When she gets stuck, Anna said that she just looks at the formula sheet and try to figure out what variables are given and what she can solve for. She also said that she does not do anything to check if her answers are correct but she sees if they sound like they could make sense. For the blowgun problem, she said she was confident because her answer sounds like it makes sense.

Skier

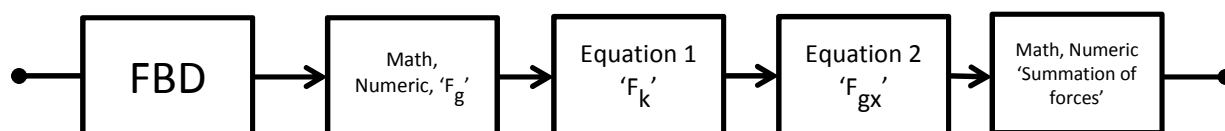


FIGURE 23. Anna’s problem solving path for the “Skier” problem.

After reading the problem, Anna drew a correct free-body diagram. She labeled all the forces and calculated the weight of the skier from the given mass. She wanted to find the kinetic friction force and knew that she would need the normal force to be able to do that. She said that the normal force should be the same as the gravitational force even though her free-body diagram indicates that the two forces are not equal. Anna was able to calculate a value for the friction force and then she resolved the gravitational force vector into components. She reasoned that since the skier is going at constant velocity, then the kinetic friction and gravitational force in the x-direction combine to equal the

tension force. She looked at her equation sheet and then she added the two values that she had mentioned. “I think this is right”, she said, “That could be how much force the tow bar has.”

In the interview, Anna explained why she started solving the problem by drawing a free-body diagram: “I guess when we were learning it, we just always started with force diagrams so I wanted to fill that all in before I started so I’ll know what I have to work with.” She said that in problems asking about forces, she would draw a force diagram but for problems like the blowgun problem, she wouldn’t need a diagram because it was not asking about forces and a diagram wouldn’t be of much help. Anna said that she thinks her answer is correct based on everything she did.

Mary

Mary is an inconsistent user of visual representations and was unsuccessful in correctly solving both interview problems. Her pre- and post-FCI scores were below the class average. We learn from her interview that she does not draw diagrams for problems that seem simple to her like the “Blowgun” problem. She drew a FBD for the “Skier” problem but she mainly engaged in numerical manipulations of given values.

Blowgun

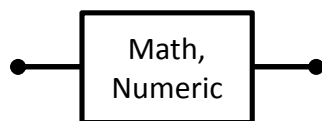


FIGURE 24. Mary’s problem solving path for the “Blowgun” problem.

Mary read the problem and then looked at her equation sheet. She said she’s trying to find time so she’ll use a velocity equation. She wrote down the given values

then tried to do numerical manipulation but she stopped and said she's trying to remember the last term [lessons from last term]. She said that she did not like the first equation that she tried to use. She punched numbers in her calculator and then she wrote down ".0857 secs". She said that she took 1.2m and divided it by the velocity to get the time. In the interview, Mary explained that usually she would try and figure out what variables were given and then she'll find an equation where she could plug in values to get what she's looking for. If she gets stuck, she said, "Usually, I try to do different things that I'm not sure that'll work just to see if I can get a logical answer." She also commented that if she were on a test, she would go through her solution and try to plug her answer back into an equation to make sure that it works but she does not usually do any checking for homework assignments.

Skier



FIGURE 25. Mary's problem solving path for the "Skier" problem.

After reading the problem, Mary drew a picture of a slope and wrote down the given values. She said she would find what 55kg is in newtons because that usually comes up. She labeled the forces in her diagram which were not in the correct directions. She also missed including the normal force. She also used the value of the coefficient of kinetic friction as the value for the kinetic friction force. The rest of her solution was mainly numerical manipulation using trigonometry. She divided the coefficient of kinetic friction by the cosine of 25 degrees and then she said that the answer she got was "not very logical". She then used the tangent function to get another number and decided that

she would use that number. She finally said, “I know what I should be doing but I can’t put it together. I should be able to find the x by using trigonometry...I should be using this [$\mu=0.120$] somehow but I don’t really know where to go from here.”

Mary used her book and then after a while she began punching numbers on her calculator and wrote down her newly calculated value in her diagram. “I’m just guessing this one,” she said, “It’s in equilibrium, they should be equal.” She multiplied 539 by 0.120 which were the numbers she had and then she used the cosine function to get another number which she declared as her final answer.

In the interview, Mary said she does not know of any way to check if her answer is correct. She also explained that for simple problems like the first one [“Blowgun” problem], she does not draw diagrams: “It was just a barrel. I’m sure there wasn’t an angle.” She said she was confident with her answer to the blowgun problem but not with the skier problem.

3.3.2 Group Comparisons

3.3.2.a Misconceptions and Limited Use of Concepts

The aggregate homework data show that the students used multiple representations in solving problems with greater use of visual representations among the students in the scaffolding group. I observed the same finding from the interview data and recognized that common misconceptions were apparent in the representations used by the students.

TABLE 14

Comparison of Problem Solving Behaviors in the Interview

How the students proceed after reading a problem	Behaviors	Scaffolding Group, % (n = 6)	Comparison Group, % (n = 6)
Blowgun	Draw a picture and label it with known values	50	17
	Write down information given from the problem	17	17
	Search for equation(s) involving variables they think they can use	33	67
Skier	Draw a picture and label it with known values	0	17
	Draw FBD/picture + FBD and identifies the forces	83	83
	Write down information + draw picture + FBD	17	0

Table 14 shows that for the “Blowgun” problem, the scaffolding may have influenced the SG students to start solving the problem by drawing a picture or writing down given values since majority of the CG students immediately searched for an equation from their equation sheet. The students who did not draw diagrams for the “Blowgun” problem identified the problem as “easy” based on its surface feature: a dart moving along a straight line.

In the “Skier” problem, although all of the SG students drew a free-body diagram, misconceptions such as the idea that the normal force is always equal to the gravitational

force led them to draw incorrect representations of the problem. The students also had the tendency to quote physics concepts with limited understanding of what they were saying. For instance, students were found to comment “forces are equal because of constant velocity” without really identifying which forces are equal. A common error made by the students is equating two forces that were not opposite and parallel to one another.

Results from the homework data supplement the findings in Table 14. There are problems in which students use visual representations without the need for scaffolding support. In solving force problems, students customarily use a visual representation in the form of a free-body diagram. When the interviewed students were asked why they drew a diagram for the “Skier” problem and not for the “Blowgun” problem, a common response was because they were taught to use a force diagram for those types of problems and that the diagram helps. Modeling the use of representations is therefore important in training students who are still novices.

The limited use or lack of use of physics concepts was observed in the interview data. Students were not influenced by the checklist to describe or explain the concepts that they used in problem solving. Although mathematical reasoning was apparent in some of the students’ solutions, the interview data suggests that majority of the students seem to believe that they are demonstrating expertise by quickly finding equations and stringing them together to get an answer more than being able to apply physics concepts. The problems were treated as basic math problems: Given these variables, find the value of x . For instance, a common error made by the students who were unable to solve the “Blowgun” problem was plugging in the given value, 14m/s , as the dart’s initial velocity

based on verbal cues in the problem without careful analysis. In the case of SG students, Mark (Appendix I) and Noah drew a diagram to depict the motion of the dart and were able to solve the problem successfully. Abby on the other hand, identified the problem as “fairly easy” thus she did not need a diagram for it. It can be argued however that she may benefit from the use of a diagram since she was not able to correctly visualize the motion of the dart. A similar case in is that of Bria (Appendix I) who automatically used -9.8m/s^2 as the acceleration of the dart through the blowgun’s barrel. A visual representation of the problem may have helped her to realize that the dart is moving horizontally along the blowgun’s barrel.

3.3.2.b Observed Problem Solving Behaviors

The interview data showed that most of the students from both groups tended to engage in a host of novice-like behaviors in problem solving rather than considering the process as a cognitive activity. I have provided a list of these behaviors and gave examples from the interview data. The rest of the cognitive interviews can be found in Appendix I.

1. Use of formula-centered means-end analysis to determine a solution path

In the interviews, a common behavior shown by students from both groups is the reliance on the equation sheet. Majority of CG students (4 out of 6) started solving the “Blowgun” problem by looking at their equation sheet. Although the SG students attempted to do a low-detail review of the problem by creating a visual or writing down given values from the problem, they would eventually refer to their equation sheet to know what to do next. While the equation sheet itself is believed to be a useful

scaffolding support in problem solving, the way it is used by the students may not help develop true expertise. Comments from the students support the quantitative data that we have gathered showing that majority of the students do not think about the concepts in solving physics problems. Instead, their confidence stems from being able to pick the right equation and carrying out the math correctly.

Students identify some problems as “easy” such as the “Blowgun” problem based on surface features. In solving “seemingly easy” problems, students were found to assume that they can be solved using a straightforward application of a single equation. When the first equation that they chose did not give them the quantity that they needed they will go back to their equation sheet and try a second one, a process that they would keep on repeating until they found something that works. The students’ response to the question on what they do when they get stuck is another proof that the students’ problem solving work is formula-centered. Students tend to go back to the equations that they have used instead of evaluating their underlying reasoning for applying the mathematical equations that they have chosen.

2. Use representations mainly based on surface features of the problem and not on concepts

Table 12 shows that the tasks for the use of visual representations seem to influence students in problems other than “force problems”. However, the presence of a visual does not have a huge impact on student performance since students who were less successful in solving problems drew visuals that are based purely on surface features such as Cat’s gun for the “Blowgun” problem and Greg’s (Appendix I) tow bar in the

“Skier” problem. The visual representations did not provide a lot of information such as the diagrams made by students from the bottom group for the “Lake” problem as shown in Table 10. For “force problems”, students may draw a free-body diagram because they acknowledge that a “slope problem” would require it. In cases when students draw a free-body diagram as a part of a known rote procedure, the diagram is most likely incorrect with the forces drawn mechanically without a thorough analysis of the described situation.

3. Too focused on the goal of getting an answer

Students seemed to be mainly concerned in getting an answer as shown by behaviors such as quickly searching for an equation or directly operating on numerical values while reporting that they are not sure about their problem-solving approach. Majority of the students from both groups did not check their answers and were satisfied as long as they were able to get an answer whose value seem to resemble values that they have seen before in class. Students were also observed to be hasty as soon as they have picked an equation. This may stem from their reliance on operational math skills since they were capable of using algebraic and trigonometric tools with ease. The students from these groups have taken algebra, trigonometry and pre-calculus courses. In the interviews, we have seen that students may break a vector just to do it because they might find some use for the vector components.

3.3.2.c Comparison of the Interview Data and Homework Data

Since the sample of students was taken from the population which gave us the quantitative data that I have discussed in the earlier sections, we can check if the data

from the homework problems are consistent with the interview data. The reason why we need to do a cross-comparison of the data is to check for general agreement. Table 15 show the number of students per code in the two interview problems. In both groups, $n = 6$.

TABLE 15

Students' Performance on the Two Interview Problems

Blowgun Problem.				
	0 No work	1 Incorrect	2 Inadequate	3 Complete
Scaffolding Group	0	4	0	2
Comparison Group	0	4	0	2
Skier Problem.				
	0 No work	1 Incorrect	2 Inadequate	3 Complete
Scaffolding Group	0	3	2	1
Comparison Group	0	2	2	2

These results seem to resemble the data from the 14 homework problems that I have presented earlier. In the “Blowgun” problem SG students used diagrams but their performance did not depart from that of the comparison group. In the “Skier” problem, both groups used a free-body diagram and differences in the quality of the diagram and misconceptions held by the students were more instrumental in determining performance than the use of the scaffolding. Figure 26 shows the students’ use of representations. Notice that the data from the sample resemble the results that we have found from the homework problems. For “force problems” such as the “Skier” problem, students from

both groups drew visual representations usually in the form of a free-body diagram as a part of their solution but for other problems that appear to be simple and easy, majority of the students tended to solely use mathematical equations. We also find once again that majority of the students do not write down explanations about the concepts that they use when generating a solution for a problem.

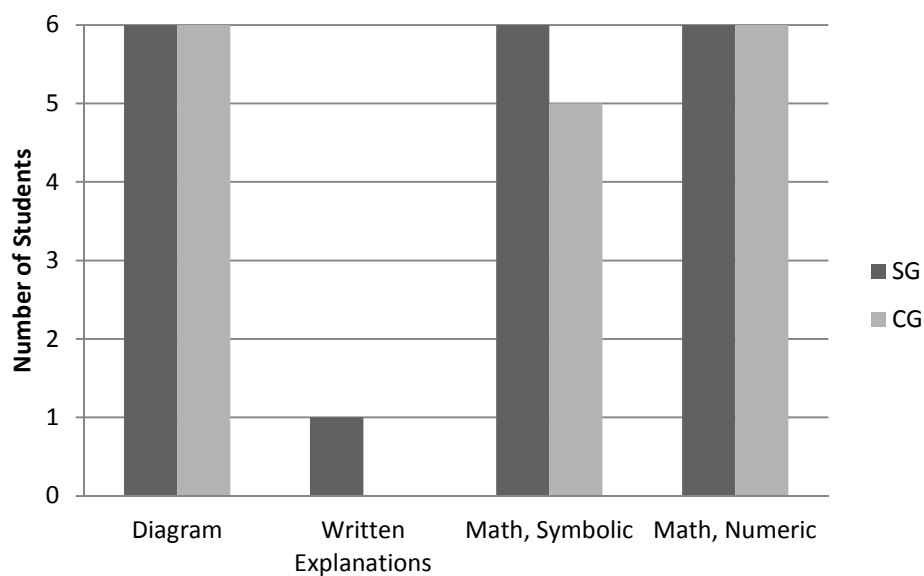
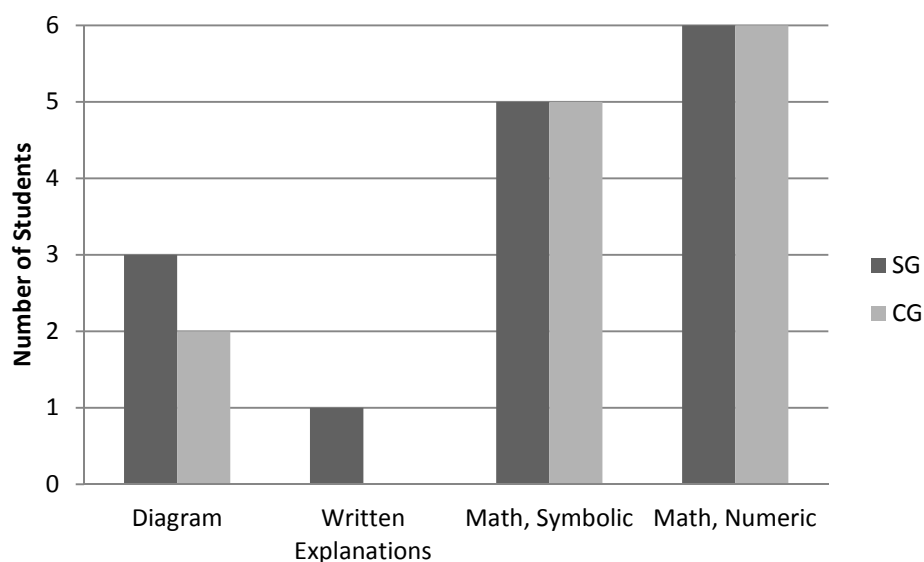


FIGURE 26. Use of representations in the interview problems (Top: “Blowgun”, Bottom: “Skier”). The figure shows a comparison of the number of students from SG and CG who showed the use of various representations in their problem solving work.

The data in this study appear to show that students who are relatively successful in completely solving “seemingly easy” problems use visual representations in constructing their solutions. Students who are less successful in solving such problems assume that a visual representation is unnecessary and would quickly jump into quantitative expressions, a typical novice-like problem solving behavior (Larkin, 1979). We should however take caution in making a general statement regarding the utility of visual representations. There might be students who are more advanced compared to their classmates in terms of knowledge and problem solving experience so the process of reaching a solution is both easy and automatic for them.

Although the scaffolding used in this study has increased the students use of visual representations, it was ineffective in eliciting verbal descriptions and explanations. There was no notable improvement in the problem solving performance by looking at the aggregate data, but both the homework and interview data show that students who were relatively successful in problem solving in their respective groups used an integrated and consistent set of representations.

CHAPTER 4

DISCUSSION

In this chapter, I will briefly summarize the research setting and procedures and then discuss the meaning of the results. The goal of this study was to explore the role of using a guided scaffolding approach for generating representation-rich solutions to problems in a high school physics course. The guided scaffolding involved the use of specific problem solving tasks, which are assumed to lead the students in using various representations (e.g., verbal, mathematical, pictorial, graphical) that may assist students' sense-making.

This study had two data gathering phases: (1) collecting problem solving work of students ($n=43$) for a period of 10 weeks and (2) interviewing selected students ($n=12$). The students were enrolled in an honors physics course that uses the Modeling Instruction curriculum. The students were in two sections with the same teacher. I arbitrarily assigned one section as the scaffolding group (SG) and the other section as the comparison group (CG). The SG students used a checklist that included eight tasks for the use of multiple representations in all homework and interview problems. In this study, the problems used were well-defined (i.e., problems with discrete representations and finite goals) and multistep, requiring both qualitative and quantitative analyses in the problem solving process.

In the previous chapter, I presented the results from the homework data and the findings from the talk-aloud interviews. In this chapter, I put together the findings of the study to answer the research questions that I have posed in the first chapter.

4.1 Claims

4.1.1 Research Question 1

How does the scaffolding strategy of using problem solving tasks affect the (a) students' use of representations, (b) students' performance in problem solving, and (c) quality of the representations they used?

Claim 1a: More students in the scaffolding group were observed to incorporate visual representations in some problems, but their use of verbal and mathematical representations did not seem to differ from the comparison group.

Findings from both the homework and interview data support this claim. Analysis of the homework data showed that students in the scaffolding group seemed to have been influenced to accomplish the tasks related to the use of visual representations in problem solving. However, the scaffolding was found to be ineffective in influencing students to use verbal representations in the form of written descriptions and explanations in their problem solving work. Very few students included written descriptions and explanations in their problem solving work. The use of mathematical representations is central to the problem solving work of the students from both groups, which implies that the prompts to use symbolic and numeric math were not needed by the students.

From the interview data, we found that majority of the students in the scaffolding groups began solving the “Blowgun” problem by drawing a picture while majority of the

students from the comparison group immediately looked for equations from their equation sheet. I also found that students who did not draw a diagram for the “Blowgun” problem considered the problem as simple and easy and they supposed that visual aids were not needed since they could simply pick the right equations to solve the problem.

It should be noted, however, that although students claimed that the problem was simple 4 out of 6 (67%) students from both groups did not solve the problem correctly. In the scaffolding group, the 3 students who did not succeed were those who did not draw a visual representation of the problem. One student (i.e. Cat) drew a picture of a gun but it was clear that the representation had not been useful to her. The 2 students who solved the problem correctly were consistent users of visual and mathematical representations. In the comparison group, all 4 of the students who did not succeed in solving the problem also did not draw a visual representation. These findings suggest that there is room for improvement and one of the first steps could be to encourage students to use visual representations to their benefit.

In problems involving forces or applications of Newton’s laws of motion, students from both groups were found to draw free-body diagrams which implies that the students solve these problems in a standard way (i.e. draw a FBD and then solve the equations) using an expected solution routine. Thus, students would use visual representations, usually a picture followed by a free-body diagram, whether they were prompted to do so or not for problems involving several forces acting on an object. From the interviews, the students confirmed they used free-body diagrams because it is a feature of the instruction they received. The homework data also showed that in the “Box”, “Sign”, and “Bricks”

problems – all of which are problems on statics - students from both groups used visual representations and solved the problem using a typical picture-FBD-equations path.

These findings are reminiscent of the results of the study by Etkina et al. (2009) where they found that reformed physics courses have a high percentage of users of FBDs (58%) for problem solving compared to traditionally taught courses (10%). In this study, we found that 100% of the SG students drew FBDs for the “Box”, “Bricks” and “I-beam” problems. Similarly, 100% of the CG students drew FBDs for the “Box” and “Sign” problems.

Claim 1b: The problem solving performance of the two groups did not seem to differ from each other.

Since the students in the scaffolding group were guided to use multiple representations in problem solving, we wanted to find out if their problem solving performance in the given study problems would improve or would differ with respect to the comparison group. The aggregate data showed that using the scoring rubric in this study, the performance of the two groups appeared to be relatively similar. When we examined the results per problem, we found that although the mean score of the scaffolding group was higher in 9 out of 14 (64%) problems, the error bars in Figure 5 indicate that the difference in means may possibly be significant only in 4 out of 14 (29%) problems. Similar results were found from the interview data. The distribution of problem-solving scores appeared to be relatively the same for the two groups (Table 13).

Within each group, however, we found that it may be possible to relate problem-solving performance with the students’ use of multiple representations. From the

homework data, we found that in both groups, students who used visual representations scored relatively higher compared to those who did not, although using multiple representations did not guarantee success in problem solving. The interview data also showed that relatively successful problem solvers used visual representations to aid their understanding of the problem and they use mathematical equations that are consistent with the picture or diagram that they have generated. These students demonstrated better conceptual understanding of the problem situation compared to those who did not acknowledge the relationship between the representations that they used.

Claim 1c: Although more students in the scaffolding group used visual representations, the quality of the representations they used did not seem to differ from the comparison group.

The findings from both the homework and interview data show that the use of visual representations does not guarantee problem solving success. Thus, although we can increase the number of users of visual representations in one class, it would not necessarily translate to an improvement of their performance as a group. Using multiple representations is an expert-like problem solving behavior and it is of course beneficial if this skill would be developed among students.

An examination of the quality of representations used by the students explains why the performance of the students remained to be relatively the same. Successful problem solvers from both groups used visual representations that are different compared to the rest of their group. Their visual representations were properly labeled, detailed, and consistent with their mathematical solution. For instance, as I have shown in our data

presentation for the “Lake” problem, the diagrams of the students who achieved a score of 3 represented the concepts of distance and displacement. In the interviews, I saw the same trend among those who succeeded in solving the interview problems especially in the “Skier” problem. On the one hand, those who successfully solved the problem had a correct and complete FBD which they constructed before they started using mathematical equations that were based on their FBD. On the other hand, those who did not succeed drew an incorrect FBD (i.e., missed one force vector, incorrect direction of at least one force vector, angle in the wrong place) or they may have drawn the correct FBD but they did not use it when constructing the mathematical part of their solution (See Anna’s interview), which meant that the diagram was drawn as if it were a part of a mechanical procedure. These findings imply that students may need guidance on constructing diagrams that would be useful in problem solving.

4.1.2 Research Question 2

How do students address the problem solving tasks in the process of solving problems? Which representations do they use and how do they use them?

Claim 2a: Students in the scaffolding group picked the tasks that they wanted to accomplish and their problem solving output revealed that they do not prefer to use verbal representations such as written descriptions and explanations.

We have seen from the homework and interview data that students rarely wrote down descriptions and explanations related to the underlying physics concepts involved in a problem. In the student interviews, we found that most students do not think about

the concepts which explain their inability to express why they are doing what they are doing. Some examples of students' comments are:

- (1) "I'm not sure what key physics concepts are relevant to this problem. I just used the formulas I know...",
- (2) "Since I have some sort of understanding of what I'm doing...I kind of overlook explaining myself" and
- (3) "I don't really think about the concepts...the diagrams help me more."

These findings suggest that there is a need for pedagogical strategies that will influence students to analyze problems in terms of concepts before jumping into quantitative expressions.

Claim 2b: Students in both groups were found to use a combination of visual and mathematical representations in problem solving but seeking and trying out equations seemed to be central in the problem solving work of most students.

We found in the interviews that although the students in the scaffolding group incorporated visual representations in their problem solving work, their next step would be to refer to their equation sheet and find the equation that might work. Some comments from the students are:

- (1) "I usually think about what I'm given then I look at my equations and think about what equations have what I'm given and what I'm trying to find",
- (2) "I usually try and figure out what they gave us, what variables, then I'll find an equation that I can plug them into to get what I'm looking for", and

(3) “I think that with the variables I’m given, the ‘quadratic’ equation is going to be the best way to solve this so that would be what I would try first and if it doesn’t work, I’m going to try something else.”

The equation sheet appeared to be a valuable scaffolding for the students. If used properly, it can be a useful aid in problem solving. When students engage in formula-seeking, the interview data revealed that they have a weak understanding of the conceptual basis of the equations. Even when they do find the right equation, they inaccurately interpret the physical meaning of the given quantities. For future work, the equation sheet can be made representation-based so that students can learn to integrate equations with a visual aid. For instance, instead of simply having a set of equations for uniformly accelerated motion, an accompanying diagram that shows parameters of motion such as initial velocity and final velocity may be included since students seemed to rely on verbal cues instead of visualizing the problem.

4.1.3 Research Question 3

What differences in misconceptions and problem solving behaviors related to the use of representations, if any, can be observed?

Claim 3: Students may construct abstract representations based on superficial features of the problem and as a part of a rote procedure.

The homework data do not give us the information about the actual problem solving process so it was necessary to observe the students and gather data as students solve and explain how they work on well-defined and multistep problems. The interviews revealed that students are less likely to succeed in solving a problem if the visual

representation that they constructed is based on superficial features of the problem and if they are generating a representation only as a part of a mechanical procedure. The goal of using a rote procedure is to get an answer which seemed to be the major concern of most of the students instead of fully understanding the problem.

In a physics course using the modeling curriculum, students learn problem solving strategies from the teacher and from their classmates. Group laboratory activities usually involve problem solving. In these small groups, students with different problem solving skills interact and it is most likely that the experienced problem solver in the group would model how a problem is solved. In this study, I have noted that the students are more concerned on finding an answer instead of presenting their understanding of the problem. Consider a case when a relatively successful problem solver quickly picks an equation and plugs in values to arrive at an answer. Inexperienced problem solvers may copy the behavior by solving their problems in the same way. Nonetheless, not all relatively successful problem solvers model this behavior. There are those who solve their problems in a detailed way with the intention of presenting their reasoning. Students can therefore develop both novice-like and expert-like behaviors when learning problem solving strategies from classmates who are considered to be relatively successful problem solvers.

As one might expect, the teacher plays a crucial role in modeling problem solving behavior. It is typical in physics classes for teachers to present an example problem that they have identified as simple and easy (i.e., seemingly easy) and encourage the students to work it out for a few minutes. After a few minutes, the teacher would then ask the class

for a number and a few would share what they were able to calculate. Some teachers may ask for a volunteer to write down their solution on the board while other teachers may quickly solve the problem on their own. If only a part of the solution is shown to the rest of the class by a student volunteer or the teacher, the other students would not realize the importance of the qualitative analysis that was done by those who successfully solved the problem. This qualitative analysis used by successful problem solvers could be a picture, a verbal description, or a mathematical expression of a key concept that serves as a decision guide for planning and evaluating a solution (Larkin & Reif, 1979).

To influence students in conducting qualitative analysis of a problem with the use of multiple representations, the behavior has to be modeled in the classroom environment even for problems that are seemingly easy based on their surface features (e.g. dart moving along a blowgun's barrel). In one of the interviews, a student explained why she drew a diagram for the "Skier" problem but not for the "Blowgun" problem: "...most likely because I was taught to go with diagrams with these kind [Skier] of problems and I wasn't for the first one [Blowgun]".

CHAPTER 5

CONCLUSIONS

This study was conducted to achieve a specific research goal and to answer definite research questions, but it remains devoted to the ultimate goal of research in science education, which is to improve teaching and learning. Using the findings that I have previously presented and discussed, I made suggestions concerning the use of instructional scaffolding on the use of multiple representations in physics problem solving. These suggestions are based on cross comparison of the findings in this study and of the previous studies on the use of multiple representations in problem solving.

5.1 Implications for Instruction

This study provided data describing how the use of multiple representations in problem solving might be supported through instructional scaffolding. I found that students responded to the problem solving tasks on multiple representations by including visual representations on their problem solving work. Also, students rarely accomplished the tasks related to the use of verbal representations. Students did not find it necessary to write down descriptions and explanations in their problem solving work. Students commonly used a combination of visual and mathematical representations in problem solving and the use of mathematical representations – symbolic and numeric – is common in both groups. In problems involving applications of Newton's laws of motion

or “force problems,” students from both groups were familiar with a routine solution which is a typical picture-FBD-equation path that they have learned in class.

The findings indicate that if students were to be influenced in using multiple representations in problem solving, the scaffolding used in this study only had the desired effect in the use of visual representations. Although more students in the scaffolding group used visual representations in response to the problem solving tasks, their performance as a group did not differ from the comparison group since the visual aids they created varied among themselves. In both groups, relatively successful students drew diagrams that are later on used in deciding which equations to use and what operations to carry out. Although students did not verbally state their reasoning in problem solving, some students stated that they were able to identify the concepts they needed and applied them in problem solving with a correct set of equations and a diagram that represented a correct translation of the verbal problem into a visual representation.

I recommend revising the list of problem solving tasks based on the findings of the study. The last four tasks on the use of mathematical representations may be discarded since the students used equations and numerical operations whether they were prompted to do so or not. In “force problems,” students used multiple representations as a result of being in a representationally rich physics class where drawing free-body diagrams has become the norm thus the need for scaffolding in the use of multiple representations may not be needed. It can also be said that the problem solving tasks would not be effective if students do not see the tasks being explicitly modeled in class lectures and discussion. For instance, it is true that problems in uniformly accelerated

motion can be easily solved by identifying the correct set of equations of motion and solving them algebraically. However, if the procedure being modeled is to simply identify what are the given values and what quantity is missing, the problem solving process becomes formula-centered and students fail to acknowledge the significance of understanding the underlying physics concepts.

High school students are still beginning learners of physics and may therefore be classified as inexperienced problem solvers; they may need guidance on how to use various representations to maximum effect in problem solving. I speculate that the students would have a positive attitude toward following the problem solving tasks if the use of visual representations and verbal explanations would be modeled through the use of sample problems. Modeling of the use of multiple representations should not be limited to problems involving the use of free-body diagrams. Students claim to mentally visualize problems and quickly identify them as easy if they know that the problem can be solved using a set of equations that is available to them. They then proceed to find an answer and behave mechanically instead of understanding the problem. Explicit instruction on analyzing situations in terms of concepts and using multiple representations may result in the acquisition of more expert-like problem solving behaviors and possibly lead to greater success. Follow-up work on how students may be supported on understanding why the use of multiple representations is useful in problem solving would likely be a productive research endeavor.

I also found in this study that the equation sheet serves as a crucial component in supporting students in the problem solving process. A problem that was identified in this

study was that students may not understand the physical meaning of variables in equations. A representation-based equation sheet might therefore lead to a better understanding of the equations. For instance, equations of motions for an object undergoing uniform acceleration may come with a diagram showing the objects' initial and final position and velocity. Also the equation sheet may come with brief explanations of underlying concepts about the conditions for the use of certain equations. The possible benefits of a representation-based equation sheet is however speculative and may therefore be explored in future work.

This study also showed that students used free-body diagrams, but they may lack the ability to interpret their diagrams and use them to construct mathematical expressions. Most students held the conception that the normal force acting on an object is always equal and opposite to the object's weight. Students also customarily drew the friction force vector in the $-x$ -axis without considering an object's direction of motion. These misconceptions in drawing free-body diagrams tell us that students tend to remember patterns from example problems modeled in class. It is therefore important for teachers to be consistent and thorough when drawing free-body diagrams. A variety of examples of mechanical systems should be used to prevent students from simply relying on pattern-seeking. Sufficient instructional time should be devoted to teaching students to draw correct free body diagrams since students are more likely to succeed in problem solving if they are able to correctly represent the problem with a free-body diagram. On the one hand, students who were relatively successful in solving problems on the applications of Newton's laws of motion acquired the habit of analyzing their diagrams and constructed

mathematical equations that were consistent with their free-body diagrams. On the other hand, students who were least successful drew free-body diagrams but focused on manipulation of equations without evaluating if their diagram is a correct representation of the described mechanical system. Presenting examples to demonstrate the meaning and application of concepts would be beneficial if teachers are aware of possible misconceptions that students may have.

5.2 Suggestions for Future Research

The implications for instruction that I have discussed in the previous section are not definitive and they can be further explored through research with a stricter control of group compositions. The findings in this study would be significant if they are found to be widespread and repeatable although the constraints in this study (i.e. use of a convenience sample and selected cognitive interviews) make broad generalizations tenuous and repetition difficult. Nonetheless, it is possible to extend the findings or repeat the study in similar contexts. Such a context would be a high school physics course using a modeling physics curriculum. The curriculum has demonstrated success in increasing conceptual gains of students as shown by above national average post-FCI scores. While conceptual knowledge is vital in problem solving, high school students are still inexperienced in applying physics concepts to problem solving. Future work on designing instructional scaffolding to help students engage in problem solving as a cognitive activity by analyzing situations in terms of concepts and employing multiple representations would be productive.

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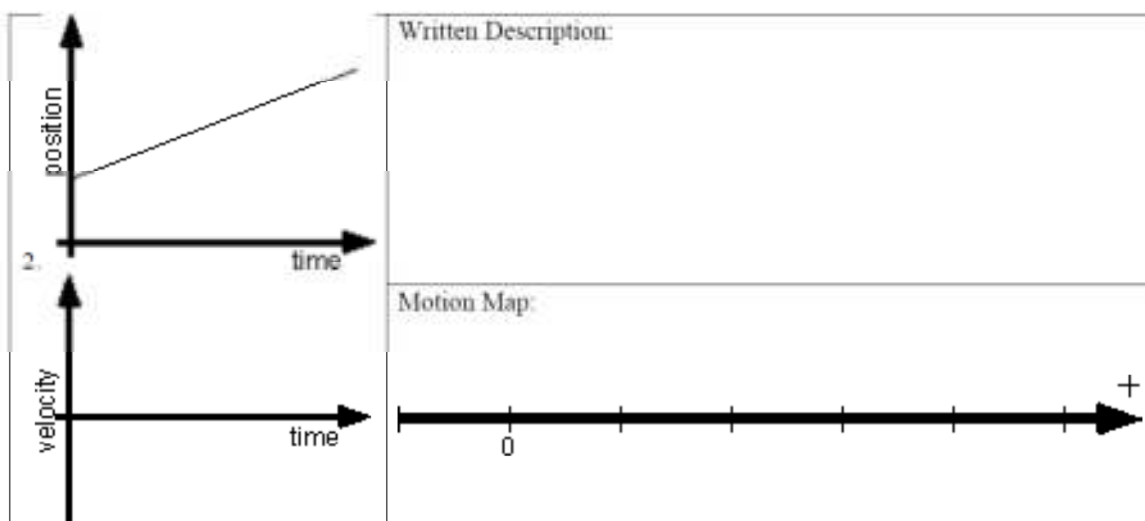
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APPENDIX A: SAMPLE ACTIVITY ON THE USE OF MULTIPLE REPRESENTATIONS IN MODELING INSTRUCTION

Constant Velocity Particle Model Ultrasonic Motion Detector Lab: Multiple Representations of Motion

Do the following for each of the situations below:

- Move, relative to the motion detector, so that you produce a position vs. time graph that closely approximates the graph shown.
- In the space provided, describe how you must move in order to produce the position vs. time graph shown in the space to the right of the velocity vs. time graph. Be sure to include each of the following in your description: starting position, direction moved, type of motion, relative speed.
- On the velocity vs. time axes, sketch the velocity vs. time graph that corresponds to the position vs. time graph shown.
- In the space provided, sketch the motion map that corresponds to the motion described in the position vs. time graph.



(This activity is abridged. The complete versions of copyrighted materials for physics teachers are available at the website of the American Modeling Teachers Association.)

APPENDIX B: STUDENT INFORMATION SHEET

Student Information**PROFILE**

Name		Year Level	
Course	<input type="checkbox"/> Physics <input type="checkbox"/> Physics Differentiated	Block	
Age		Sex	

Encircle the letter of your answer to the following questions.

1. How well **prepared** do you feel to deal with the subject matter of physics?
 - a Totally unprepared
 - b Unprepared
 - c Somewhat prepared
 - d Prepared
 - e Very well prepared
2. What was the last math course you completed?
 - a Algebra
 - b Geometry
 - c Trigonometry
 - d Pre-calculus
 - e Calculus
3. When did you take your most recently completed math course?
 - a Last semester
 - b Two semesters ago
 - c Last year
 - d More than 2 years ago
4. Are you enrolled in a math course this semester?
 - a No
 - b Yes
5. How many total course units are you taking this semester?
 - a 1-3
 - b 4-6
 - c 7-9
 - d 10-12
 - e More than 12

APPENDIX C: MARYLAND PHYSICS EXPECTATIONS SURVEY

EXPECTATIONS IN PHYSICS

Here are 34 statements which may or may not describe your beliefs about this course. You are asked to rate each statement by circling a number between 1 and 5 where the numbers mean the following:

1: Strongly Disagree	2: Disagree	3: Neutral	4: Agree	5: Strongly Agree
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Answer the questions by circling the number that best expresses your feeling. Work quickly. Don't overelaborate the meaning of each statement. They are meant to be taken as straightforward and simple. If you don't understand a statement, leave it blank. If you understand, but have no strong opinion, circle 3. If an item combines two statements and you disagree with either one, choose 1 or 2.

1	All I need to do to understand most of the basic ideas in this course is just read the text, work most of the problems, and/or pay close attention in class.	1	2	3	4	5
2	All I learn from a derivation or proof of a formula is that the formula obtained is valid and that it is OK to use it in problems.	1	2	3	4	5
3	I go over my class notes carefully to prepare for tests in this course.	1	2	3	4	5
4	"Problem solving" in physics basically means matching problems with facts or equations and then substituting values to get a number.	1	2	3	4	5
5	Learning physics made me change some of my ideas about how the physical world works.	1	2	3	4	5
6	I spend a lot of time figuring out and understanding at least some of the derivations or proofs given either in class or in the text.	1	2	3	4	5
7	I read the text in detail and work through many of the examples given there.	1	2	3	4	5
8	In this course, I do not expect to understand equations in an intuitive sense; they must just be taken as givens.	1	2	3	4	5
9	The best way for me to learn physics is by solving many problems rather than by carefully analyzing a few in detail.	1	2	3	4	5
10	Physical laws have little relation to what I experience in the real world.	1	2	3	4	5
11	A good understanding of physics is necessary for me	1	2	3	4	5

	to achieve my career goals. A good grade in this course is not enough.	
12	Knowledge in physics consists of many pieces of information each of which applies primarily to a specific situation.	1 2 3 4 5
13	My grade in this course is primarily determined by how familiar I am with the material. Insight or creativity has little to do with it.	1 2 3 4 5
14	Learning physics is a matter of acquiring knowledge that is specifically located in the laws, principles, and equations given in class and/or in the textbook.	1 2 3 4 5
15	In doing a physics problem, if my calculation gives a result that differs significantly from what I expect, I'd have to trust the calculation.	1 2 3 4 5
16	The derivations or proofs of equations in class or in the text has little to do with solving problems or with the skills I need to succeed in this course.	1 2 3 4 5
17	Only very few specially qualified people are capable of really understanding physics.	1 2 3 4 5
18	To understand physics, I sometimes think about my personal experiences and relate them to the topic being analyzed.	1 2 3 4 5
19	The most crucial thing in solving a physics problem is finding the right equation to use.	1 2 3 4 5
20	If I don't remember a particular equation needed for a problem in an exam there's nothing much I can do (legally!) to come up with it.	1 2 3 4 5
21	If I came up with two different approaches to a problem and they gave different answers, I would not worry about it; I would just choose the answer that seemed most reasonable. (Assume the answer is not in the back of the book.)	1 2 3 4 5
22	Physics is related to the real world and it sometimes helps to think about the connection, but it is rarely essential for what I have to do in this course.	1 2 3 4 5
23	The main skill I get out of this course is learning how to solve physics problems.	1 2 3 4 5
24	The results of an exam don't give me any useful guidance to improve my understanding of the course material. All the learning associated with an exam is in the studying I do before it takes place.	1 2 3 4 5
25	Learning physics helps me understand situations in my everyday life.	1 2 3 4 5
26	When I solve most exam or homework problems, I	1 2 3 4 5

	explicitly think about the concepts that underlie the problem.	
27	"Understanding" physics basically means being able to recall something you've read or been shown.	1 2 3 4 5
28	Spending a lot of time (half an hour or more) working on a problem is a waste of time. If I don't make progress quickly, I'd be better off asking someone who knows more than I do.	1 2 3 4 5
29	A significant problem in this course is being able to memorize all the information I need to know.	1 2 3 4 5
30	The main skill I get out of this course is to learn how to reason logically about the physical world.	1 2 3 4 5
31	I use the mistakes I make on homework and on exam problems as clues to what I need to do to understand the material better.	1 2 3 4 5
32	To be able to use an equation in a problem (particularly in a problem that I haven't seen before), I need to know more than what each term in the equation represents.	1 2 3 4 5
33	It is possible to pass this course (get a "C" or better) without understanding physics very well.	1 2 3 4 5
34	Learning physics requires that I substantially rethink, restructure, and reorganize the information that I am given in class and/or in the text.	1 2 3 4 5

APPENDIX D: NOTE ON THE FORCE CONCEPT INVENTORY

The Modeling Instruction staff at Arizona State University denies permission to include the FCI in any doctoral dissertation or master's degree thesis. Interested parties can request a download password from the Modeling Instruction staff and access the FCI from the following URL: <http://modeling.asu.edu/R&E/Research.html>

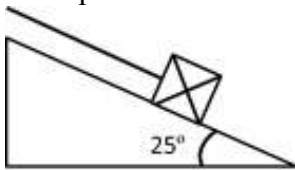
APPENDIX E: EXPERT RESPONSES TO MPEX SURVEY ITEMS

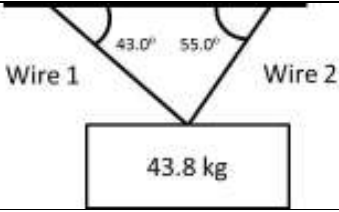
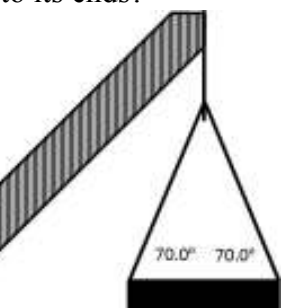
The University of Maryland Physics Education Research Group gave the survey to a group of experienced university faculty committed to reforming their teaching to increase its effectiveness and have used this group's response as their definition of "expert". This group shows a strong consistency (>90%) on most of the survey items. The response "A" indicates “agree or strongly agree” - a choice of numbers 4 or 5. The response "D" indicates “disagree or strongly disagree” - a choice of numbers 1 or 2. Where the respondents did not agree at the 85% level, the item is shown in parentheses and the majority response is shown.

Expert Responses				
1 D	8 D	15 D	22 D	29 D
2 D	9 (D)	16 D	23 D	30 A
3 A	10 D	17 D	24 D	31 A
4 D	11 A	18 A	25 A	32 A
5 A	12 D	19 D	26 A	33 D
6 A	13 D	20 D	27 D	34 (A)
7 (A)	14 D	21 D	28 D	

APPENDIX F: LIST OF PROBLEMS USED

Study Problems

Tag	Problem Text
1 Lake	One afternoon, a couple walks three-fourths of the way around a circular lake, the radius of which is 1.50 km. They start at the west side of the lake and head due south at the beginning of their walk. (a) What is the distance they travel? (b) What are the magnitude and direction (relative to due east) of the couple's displacement?
2 Earth	The earth moves around the sun in a nearly circular orbit of radius 1.50×10^{11} m. During the three summer months (an elapsed time of 7.89×10^6 s), the earth moves one-fourth of the distance around the sun. (a) What is the average speed of the earth? (b) What is the magnitude of the average velocity of the earth during this period?
3 Jetliner	A jetliner, traveling northward, is landing with a speed of 69 m/s. Once the jet touches down, it has 750 m of runway in which to reduce its speed to 6.1 m/s. Compute the average acceleration (magnitude and direction) of the plane during landing.
4 Blowgun	The length of the barrel of a primitive blowgun is 1.2 m. Upon leaving the barrel, a dart has a speed of 14 m/s. Assuming that the dart is uniformly accelerated, how long does it take for the dart to travel the length of the barrel?
5 Astronaut	An astronaut on a distant planet wants to determine its acceleration due to gravity. The astronaut throws a rock straight up with a velocity of +15 m/s and measures a time of 20.0 s before the rock returns to his hand. What is the acceleration (magnitude and direction) due to gravity on this planet?
6 Two Players	Two soccer players start from rest, 48 m apart. They run directly toward each other, both players accelerating. The first player has an acceleration whose magnitude is 0.50 m/s^2 . The second player's acceleration has a magnitude of 0.30 m/s^2 . (a) How much time passes before they collide? (b) At the instant they collide, how far has the first player run?
7 Box	The box shown in the figure is held by a rope at rest on a frictionless surface. The weight of the box is 25 N. How much force is applied by the rope? 
8 Sign	A 43.8-kg sign is suspended by two wires, as the drawing shows. Find the tension in wire 1 and in wire 2.

	 <p>Wire 1 Wire 2</p> <p>43.0° 55.0°</p> <p>43.8 kg</p>
9 Bricks	A 100-kg pile of bricks is being pulled at a constant speed across a level floor at an angle of 40° . If a 300-N force is applied, what is the value of the normal force?
10 I-beam	<p>The steel I-beam in the drawing has a weight of 8.00 kN and is being lifted at a constant velocity. What is the tension in each cable attached to its ends?</p>  <p>70.0° 70.0°</p>
11 Rock	A rock of mass 45 kg accidentally breaks loose from the edge of a cliff and falls straight down. The magnitude of the air resistance that opposes its downward motion is 250 N. What is the magnitude of the acceleration of the rock?
12 Black Belt	A person with a black belt in karate has a fist that has a mass of 0.70 kg. Starting from rest, this fist attains a velocity of 8.0 m/s in 0.15 s. What is the magnitude of the average net force applied to the fist to achieve this level of performance?
13 Rocket	A rocket blasts off from rest and attains a speed of 45 m/s in 15 s. An astronaut has a mass of 57 kg. What is the astronaut's apparent weight during takeoff?
14 Baseball	A 92-kg baseball player slides into second base. The coefficient of kinetic friction between the player and the ground is $\mu_k = 0.61$. (a) What is the magnitude of the frictional force? (b) If the player comes to rest after 1.2 s, what is his initial speed?

Interview Problems

Tag	Problem Text
1 Blowgun	The length of the barrel of a primitive blowgun is 1.2 m. Upon leaving the barrel, a dart has a speed of 14 m/s. Assuming that the dart is uniformly accelerated, how long does it take for the dart to travel the length of the barrel?

2 Skier	A skier is pulled up a slope at a constant velocity by a tow bar. The slope is inclined at 25.0° with respect to the horizontal. The force applied to the skier by the tow bar is parallel to the slope. The skier's mass is 55.0 kg , and the coefficient of kinetic friction between the skis and the snow is 0.120 . Find the magnitude of the force that the tow bar exerts on the skier.
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The “Box” and “Bricks” problems are taken from the instructor’s teaching unit. All the other problems are taken from Cutnell & Johnson’s Physics, 5th Edition.

APPENDIX G: CHECKLIST OF PROBLEM SOLVING TASKS

Output	Specific Tasks	Completed	
		Yes	No
Visual Representation	Draw a diagram(s) that represents your understanding of the problem (chart, graph, sketch, free-body diagram, picture, arrows)		
	Label the diagram(s) with symbols of physical quantities given in the problem		
Reasoning	Identify the key physics concepts that you think are relevant to solving the problem		
	Briefly explain how you will use the key concepts in your procedure for solving the problem and evaluating if your answer is correct		
Mathematical Model	Identify the equations that you would need		
	Derive the mathematical model that you would need to use in order to find a numerical solution		
Numerical Solution	Identify the numerical values of the physical quantities given in the problem		
	Perform the appropriate operations on your derived mathematical model		

APPENDIX H: INTERVIEW PROTOCOL

I. Introduction

II. IRB Forms

III. Think Aloud Interview

1. Interviewer: I will be giving you two problems to work on. You can take as much time as you like to solve the problems. You are also free to stop anytime. Remember that you are not being evaluated in this activity. I want you to feel comfortable and solve the problems as you usually do in in your physics class. A camcorder is set up to take a video and audio record of your problem-solving work and our conversation. Our faces will not be captured in the video. The video and audio record will be used entirely for note-taking purposes. I will need you to talk aloud and explain to me what you are doing in every step of the problem-solving process.

Let me know when you are ready.

2. Interview Problems

IV. Probing Questions

1. How do you typically solve a problem? Where do you start?
2. How do you accomplish the tasks in the checklist?
3. What are your purposes for drawing pictures and diagrams?
4. What do you do when you get stuck?
5. How do you know if your answer is correct?

APPENDIX I: COGNITIVE INTERVIEWS

A. Scaffolding Group

MarkBlowgun

After reading the problem, Mark drew a picture based on the numbers given in the “Blowgun” problem. He labeled the picture with the numbers without identifying what quantities they are (i.e. final velocity, displacement). It is apparent in his drawing that he did not recognize the given velocity as the velocity of the dart after traveling the length of the barrel. He drew a dart on the leftmost end of his representation of the barrel and drew an arrow to show that it is moving to the right. He said, “We know that the bullet is moving down a barrel at 14m/s...” His statement tells us that he thought that the dart was moving at a constant velocity.

Mark read the problem again and said that he needs his formula sheet. He said he needs to find the acceleration, which meant that he realized he cannot directly find the time it takes for the dart to travel the length of the barrel without looking for the acceleration first. He said, “I’m thinking I’ve gotta use ‘v-vax.’” He correctly identified an equation for uniformly accelerated motion that he could use to compute for the constant acceleration. In using this equation, he also correctly identified that the dart’s initial velocity was zero. He quickly worked through the equation and found the value of the acceleration. He said, “We have the acceleration to plug in to v-vat.” This statement confirms that he knew what to look for and he had a clear plan to find it.

Mark successfully found the value for time and did not do any checking of his work. He checked all but one item on reasoning in the list of problem solving tasks. He knew that he did not explain how he used physics concepts in solving and evaluating. When asked why he did not do the specific task on reasoning, he said “I don’t know ‘cause I think since I have some sort of understanding of what I’m doing, so I don’t really, I kind of overlook explaining myself.”

Skier

Mark read the problem and began his solution by drawing a force diagram. First, he solved for the gravitational force acting on the skier and then labeled the diagram with the value that he calculated. He said, “That’s the 539-N downward force.” He then drew the friction force vector in the $-x$ -axis of his force diagram. He looked at his equation sheet and wrote down the equation for kinetic friction. He then drew the applied force vector at 25 degrees relative to the positive x -axis. He then claimed that the normal force equals the gravitational force and used this reasoning to solve for the kinetic friction force. He labeled his diagram with his calculated value for friction. Mark proceeded by claiming that since the skier is at constant velocity, the kinetic friction force is equal to the x -vector [x -component of the applied force]. He used trigonometry to find the magnitude of the applied force and arrived at an answer. He then completed the checklist of problem solving tasks.

In the interview with Mark, after he had solved the two problems, he said that he usually likes to draw first to get a better picture of what he is thinking. When asked how he would know if his answers are correct, he said “I really don’t because I’m not too

secure with these types of problems. I'm usually pretty confident with my answers but not right now." Nonetheless, he said he was confident with his solution in the "Blowgun" problem, but not very sure about the "Skier" problem. In response to the question about what he does when he gets stuck, he said he would usually go to his formula sheet and see what formulas would work with the numbers that he had or he would get back to the book and try to read.

Bria

Blowgun

Bria said that the way she starts solving a problem is by writing down all the given information. First, she wrote down the given values. Second, she identified and wrote down the key concept in the problem which is "uniform acceleration". Finally, she wrote down the target variable. She mistakenly identified 14m/s as the initial velocity of the blow dart. After writing down all the information she could get from the problem, Bria said, "I would next go to my formula sheet and find an equation that has these variables and like, whatever the thing I'm trying to find is."

Bria scanned her equation sheet and said that the 'quadratic' would be the best way to solve the problem so she would try using that equation first. She also said that if it doesn't work, she would try something else. She copied the equation and plugged in the values she had. She mistakenly plugged in 9.8m/s^2 as the acceleration of the dart and she was able to get two values for time which are both positive - 0.088 and 2.77s. Bria said that by just using her reasoning, she would choose 2.77s because it is the more logical answer. In the interview after she had solved the problem, she said that usually one of the

values like 0.088 would be negative and one of them would be positive and she would always choose the positive one. She then went back to her solution to check her math. When she got the same values, she said that the problem is different from other problems that she had done. When she chose her final answer, she said “Usually the answers are a lot closer to that [2.77s] and there’ll be a smaller number that’s negative and so I’d choose the one that seems more logical.

Bria accomplished the checklist and said that she didn’t draw any kind of diagram because she is not as much as a visual learner and in that particular problem, she could just visualize more easily in her head. She said that it was not necessary to draw a picture. She also said that she identified the concepts that were necessary to solve the problem by remembering what a formula was used for and thinking about how similar problems were solved in class. She said that although she did not explain the concepts, she used them in her procedure.

When asked what she does when she gets stuck, Bria said, “The first thing I would do is go back to my calculator and see if it was like a mathematical typo, something I didn’t enter correctly in my calculator and then if that isn’t the problem then I would go back and see if the equation that I picked was the right one...and choose a different equation that would fit the problem.” Bria said that she was somewhat confident with her answer because it seemed pretty reasonable but she also said that she felt a little bit off about one of the values from the ‘quadratic’ not turning out to be negative.

Skier

Bria started working on the problem the same way. After reading it, she wrote the given values and then she drew a picture. She said, “In this one, I’ll draw a picture for just because it’s easier to visualize that way.” She labeled the picture with the information available to her and she identified the target variable. She then drew a free-body diagram. She said she would translate all the information to the diagram. She missed drawing the friction force vector and she drew the angle in the wrong place. She evaluated her diagram for a moment and realized her mistake about the angle. However, she was not able to identify the right direction of the angle. In her mathematical expression for the sum of all forces, she was not able to include all the forces. She drew a picture of a right triangle for vector components and then she solved the problem quickly using trigonometry.

In the interview after she had solved the problem, Bria said, “I did a diagram ‘cause that’s easier when we’re like, you’re given like, this type of a problem and the angle, and drawing a force diagram definitely helps to solve that.” She said she used “force concepts” like knowing what the different forces are and how to label them, where they go on the force diagram, and how to set that up. She explained that “since there is a constant velocity of the skier, so there is no acceleration, so the forces are balanced, so all the forces in the x- and y- direction will equal zero.”

When asked how she would know if her answer is correct, she said that she would first think about it if it seems logical in relation to the other given values and if she had another equation, she could also use that. She also said that another thing that she would

do is to check the trigonometry part: “I’ll do sine instead of cosine to kind of check on my math...” Bria said that she was confident with her solution.

Luke

Blowgun

Luke read the problem and then he looked at his equation sheet. He explained that he got a velocity and a distance and he needs to find time so he picked a formula that would help him find what he needs. He then divided 1.2m by 14 and then he wrote down his final answer which is 0.0857 s. To check if his answer is correct, Luke said that he can plug back his answer to the equation but there’s not a ton of ways to verify if his answer is correct unless there’s another formula that he could use. He said that he is confident with his answer.

Skier

After reading the problem, Luke drew a force diagram. He calculated the gravitational force from the mass and labeled all the forces in his diagram. The forces in his diagram are not drawn in the correct directions and he also said that the normal force is always equal to the gravitational force. He calculated the frictional force by plugging in values he had and equated it to the x-component of the applied force.

In the interview, Luke said that if he gets stuck, he would look over his notes and figure out what process he needs to go through and if it happened during a test, he would look at his formula sheet and see if there’s a different formula he needs to use. When asked why he only drew a diagram for the second problem, he said, “In this problem [Blowgun] I had all the variables I needed and I just needed to pick an equation so I did

not need to draw what I was trying to find. In this one [Skier] I had forces so I needed to draw a force diagram...” Luke said that he was confident with his answer in the first problem but not so sure about the second one because problems similar to the “Skier” problem were always a little bit trickier for him.

B. Comparison Group

Margaret

Blowgun

After reading the problem, Margaret looked at her equation sheet and said, “I know I need to use like these equations for displacement and things like that so I’m going to use the ‘quadratic’ because I have the displacement and final velocity.” She did not copy the equation. Instead, she plugged in the values right away to her chosen equation (i.e. the ‘quadratic’) until she realized that she had two variables missing. She tried the ‘v-vat’ equation but just like the ‘quadratic’, she ended up with an equation with two variables. She then finally used the ‘v-vax’. She explained that it was the only equation that has both the final velocity and the displacement. At that point, she had a clear plan. She said she would find the acceleration and then use that to find the time. Margaret quickly solved the problem and made a math error although her procedure could have given her the right answer.

Margaret said that when she solves problems, she usually thinks about the given values and then she looks at her equation sheet to find which equations have the variables she has with the variable that she’s trying to find. She also said that sometimes she has to write out the equations to visualize but usually she just thinks about the equations.

Margaret said that she is usually confident about her answers so she does not do any checking unless she feels uneasy, in which case she would plug numbers back in.

Skier

Margaret started by drawing a picture of the slope and labeled it with the angle given in the problem. She continued reading the problem and then she said that what she usually does is start with a force diagram. She drew a correct force diagram and quickly labeled it with forces that she could calculate from the given values. Margaret had a clear plan. She quickly solved for components she needed, found the normal force and then used it to find the fictional force. Margaret did not mention anything about the skier moving at constant velocity although when she explained her solution after she had solve it, she said that everything was in equilibrium and that she needed to find the forces in the -x-axis so she could find the towing force. She said, “They equal each other and stuff”. Maggie was able to get the correct answer.

When asked what she does when she gets stuck, she said that she tries to go over her work, find where she could have gone wrong, or use a different equation that would work better. She said that she was sure with both of her answers and the reason why she drew a diagram for the second problem was because she was taught to go with diagrams with “these kind of problems” and she wasn’t taught to do so for the first one. She then added that the diagram helps her visualize and that she likes to mark up things like angles and forces.

Marcus

Blowgun

After reading the problem, Marcus looked at his equation sheet and began writing down the given values and the target variable. He scanned his equation sheet again and said that he was looking for the right equation to plug in the displacement and velocity in order to find the time. He decided that he would use the 'quadratic'. (Later in the interview, he said, "I thought I would use the quadratic equation but then I realized I would need acceleration."). He plugged in the values he had and noticed that there were two unknown variables in the equation so he stopped and once again wrote down the values that he had and went back to his equation sheet. He then said, "We could use 'v-vax'". After this step, he quickly worked through the rest of the problem. He found the acceleration and plugged it in the 'v-vat' equation to get the time. Marcus was able to get the correct answer. When asked if he does anything to know if his answer is correct, he said he usually checks to see if it would be reasonable for the situation and that in the case of the blowgun, 0.17 seconds would be reasonable for the dart to cover 1.2 meters.

Skier

Marcus started by drawing a correct free-body diagram. He identified all the forces acting on the skier and labeled his diagram with all the information available to him. He examined his diagram and said that he could break the gravitational force into two parts. He calculated the magnitude of the gravitational force and added the information on the diagram. He then wrote down mathematical expressions for the sum of all forces along the x-axis and along the y-axis relative to his diagram. He then quickly worked through the rest of the problem explaining what he was doing in every step of the way.

Marcus was able to get the correct answer. He was asked if there was a point in the problem where he got stuck and he said, “When I was originally drawing the diagram I had to think it over a little bit but after that there’s a clear path.” He also said that when he gets stuck in solving a problem, he would usually re-read the question multiple times until he understands what it is asking. Marcus said that the diagram helped him to know which forces oppose each other and that since there was a given slope, he realized that he had to find different pieces. He also said that he does not draw diagrams for problems like the “Blowgun” problem. When asked if he was confident with his solutions, he said he was sure with the second one but not that sure with first problem.

Greg

Blowgun

Greg started by identifying the numbers in the problem and writing down the information. When he saw 14m/s , he said, “I see that and I instantly think velocity”. He read the rest of the problem and identified the target variable which is time. He then said he would go to his equation sheet and look for something that is missing time. He then chose an equation for constant velocity which does not apply to the situation since the problem stated that the dart is uniformly accelerated. He then plugged in the values he had and simply divided the given displacement by the velocity. He said, “I don’t think this is what I wanna be doing. I don’t know. I’ll work it through then maybe if I don’t like it, I’ll revise.” When he got an answer, he was unsatisfied with it and mumbled “uniformly accelerating” and then he said, “That means that the dart is not moving at a constant speed.” He read the problem again and drew a picture of a blowgun’s barrel. He

then said that it doesn't take long to go through the blowgun especially if it has a 14m/s -velocity so he decided to go along with his answer. When he explained his answer, he said that he drew the diagram to think about the blowgun because he got a very small value for time but then when he thought about it with the visual he claimed that his answer could be somewhat reasonable. He said that to solve problems, he normally starts by writing down the given values, and then he looks at his formula sheet to find an equation that he could use.

Skier

Greg drew a slope and labeled it with the given angle. He then wrote down the rest of the available information like the mass of the skier and the coefficient of kinetic friction. He read the problem again and said, "Okay, so I'm looking for a force." He looks at his equation sheet and scanned it and then he said, "This doesn't work". He read the problem again and then he calculated the gravitational force on the skier using the given mass. He drew a long arrow from the calculated value [539N] to the slope and said, "That's gonna go right here." He read the problem again and drew a tow bar attached to the slope. He said he was a little stuck. He then began using the numbers without any clear purpose until he said, "Ah, I'm lost. I can't tell you." He then picked two numbers and added them together and said, "I know this is wrong but this would be my final answer. I know it's not correct."

When asked to explain his solution, he said that he was looking for force and when he looked at his equation sheet, he wanted an equation that he can use to find force. He said he saw the equation for work but the problem did not give him distance or a

velocity, or acceleration, so he thought of other ways to attack the problem and figured out that in many sample problems they did in class, they'd use the mass and "find it in newtons" and then they'd usually find "this side or this side [i.e. vector components]". If he knew which equation to use, he said that he could plug the numbers back in as a way to check if his answer is correct.

Greg was asked to explain the use for his diagrams. He said that when he thinks of things with slope, he thinks of the picture of a slope and then he tries to work on the problem from that. In case he is unsure about what to do, he said, "I have to like, draw, physically draw a diagram like a car, like a tow hook, see if that helps me out and if that doesn't help me out anymore, then I usually plug in other things and look at answers that are reasonable."

APPENDIX J: OFFICIAL APPROVAL LETTER FOR IRB PROJECT #13702



November 21, 2013

Lyrice Lucas
Teaching, Learning and Teacher Education
311 Husker Hall Lincoln, NE 68503-2998

Elizabeth Lewis
Teaching, Learning and Teacher Education
212 HENZ, UNL, 68588-0355

IRB Number: 20131113702 EX
Project ID: 13702
Project Title: Supporting Representation-rich Problem Solving in High School Physics

Dear Lyrice:

This letter is to officially notify you of the certification of exemption of your project by the Institutional Review Board (IRB) for the Protection of Human Subjects. It is the Board's opinion that you have provided adequate safeguards for the rights and welfare of the participants in this study based on the information provided. Your proposal is in compliance with this institution's Federal Wide Assurance 00002258 and the DHHS Regulations for the Protection of Human Subjects (45 CFR 46) and has been classified as Exempt Category 2.

You are authorized to implement this study as of the Date of Exemption Determination: 11/21/2013.

1. The stamped and approved informed consent documents have been uploaded to NUgrant (file with -Approved.pdf in the file name). Please use these documents to distribute to participants. If you need to make changes to the documents, please submit the revised documents to the IRB for review and approval prior to using them.

We wish to remind you that the principal investigator is responsible for reporting to this Board any of the following events within 48 hours of the event:

- * Any serious event (including on-site and off-site adverse events, injuries, side effects, deaths, or other problems) which in the opinion of the local investigator was unanticipated, involved risk to subjects or others, and was possibly related to the research procedures;
- * Any serious accidental or unintentional change to the IRB-approved protocol that involves risk or has the potential to recur;
- * Any publication in the literature, safety monitoring report, interim result or other finding that indicates an unexpected change to the risk/benefit ratio of the research;
- * Any breach in confidentiality or compromise in data privacy related to the subject or others; or
- * Any complaint of a subject that indicates an unanticipated risk or that cannot be resolved by the research staff.

This project should be conducted in full accordance with all applicable sections of the IRB Guidelines and you should notify the IRB immediately of any proposed changes that may affect the exempt status of your research project. You should report any unanticipated problems involving risks to the participants or others to the Board.

If you have any questions, please contact the IRB office at 472-6965.

Sincerely,

A handwritten signature in blue ink that reads "Becky R. Freeman".

Becky R. Freeman, CIP
for the IRB

